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Design of a MATLAB[®] Image Comparison and Analysis Tool for Augmentation of the Results of the Ann Arbor Distortion Test

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14. ABSTRACT The Ann Arbor distortion test, an important test in assessing the quality of an optical sample, provides mostly subjective, qualitative results. The purpose of this project was to use current image analysis technology to analyze distortion images and standards and to create quantitative results that would remain constant independent of the user of the device. The final output was an executable file that runs a MathWorks, Inc., MATLAB code and provides numeric results on various qualities tested with the Ann Arbor distortion test.						
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Introduction

In the evaluation of the optical quality of various transmissive components (e.g., a lens, visor, windscreen or transparent display), one important test is optical distortion. Distortion is one form of optical aberration and is defined as the deviation from rectilinear projection, i.e., a projection in which straight lines in a scene remain straight in an image, as viewed through the sample component(s). This deviation is due to spatial variation in optical power across the sample.

One commonly employed device for evaluating the presence and extent of optical distortion is the Ann Arbor distortion tester¹ (figure 1). This device works by identifying regions of changes in lens power present when a standard (zero distortion) grating pattern is viewed through the optical sample. These distortions can include: changes in the number of lines, changes in the distance between lines, straightness of the lines, and inconsistencies in linewidth (e.g., areas get wider or so thin that they seem to vanish).

The Ann Arbor distortion test is considered essential to testing optical quality and is preferred for its speed of testing and for the large area over which it provides a topographical overview of lens power and surface properties. This test also allows optical defects in the sample to be easily located and marked for further evaluation.

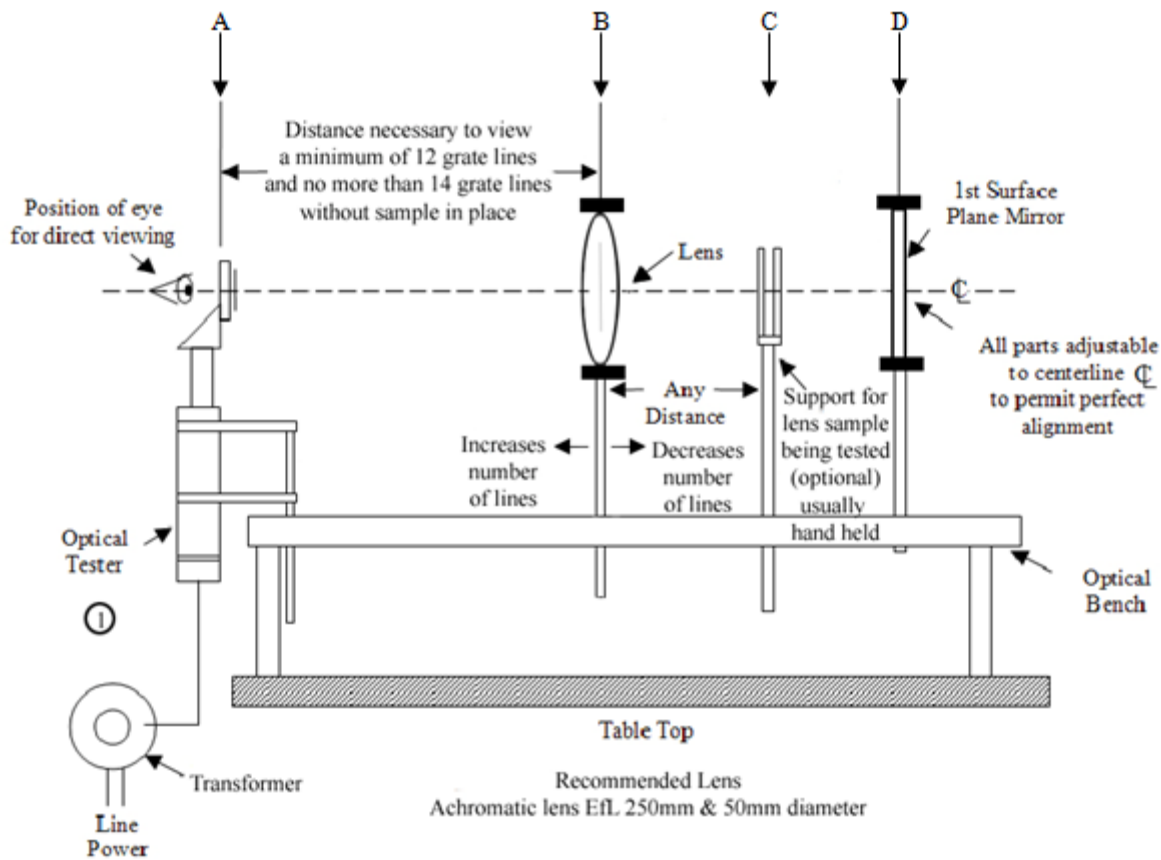
The major drawback to the Ann Arbor distortion test is its subjectivity. The determination of the amount of distortion present in an optical sample is made by visually comparing the standard grating pattern, as viewed by an observer, with the sample in place to a set of known pass/fail distorted/undistorted images provided in a predetermined specification document; for the U.S. Army, the specification is Military Standard, MIL-V-43511D Detail Specification Visors, Flyer's Helmet, Polycarbonate. This comparison is very subjective and the determination of the level of distortion present in the sample depends greatly on the experience of the observer.

Presented herein is a preliminary design of a proposed automated rule-based technique using off-the-shelf image analysis software to capture, analyze, and quantify the level of distortion present in images produced by the Ann Arbor distortion tester, reducing observer variability and the need for an experienced observer.

Background

The Ann Arbor distortion tester consists of four main parts: the optical tester, the tester lens, the sample support fixture, and the mirror (figure 1). The optical tester (position A, figure 1) contains a light source and a line grating consisting of 50 lines. The lens at position B is an achromatic 50-mm diameter lens with a 182-mm focal length. The support fixture for the optical

¹ Model E Distortion Tester available from Data Optics, Inc. at their website www.dataoptics.com, or by phone at 800-321-9026.



DISTORTION TESTER

1. Model "E" Distortion Tester or equivalent, with a 50 to 60 line grating or equivalent (obtainable from Data Optics Inc, 115 Holmes Road, Ypsilanti, Michigan, 48198-3020, telephone 1-800-321-9026).

Figure 1. Ann Arbor distortion tester.

sample (position C, figure 1) normally is used only when the optical sample needs to be held in a certain position for photographic documentation; otherwise, the sample usually is hand-held for ease of rotation and positioning during active observation. Finally, the front-surface mirror (position D, figure 1) is positioned to reflect light from the optical tester directly back to the position of the observer's eye. A camera is frequently placed at the eye position to document results.

When aligning the components on the optical bench, the first step is to ensure that all of the components are at approximately the same height. Once this alignment is achieved, the next step is to turn on the illumination source and adjust the angle (rotation and tilt) of the mirror such that the light returns through the system to the observer's eye (or to the camera). Note: If the lines that are visible without an optical sample are not straight but rather bowed inward towards the center of the image, the Ann Arbor focusing lens is most likely positioned backwards and must be rotated 180 degrees front-to-back (figure 2).

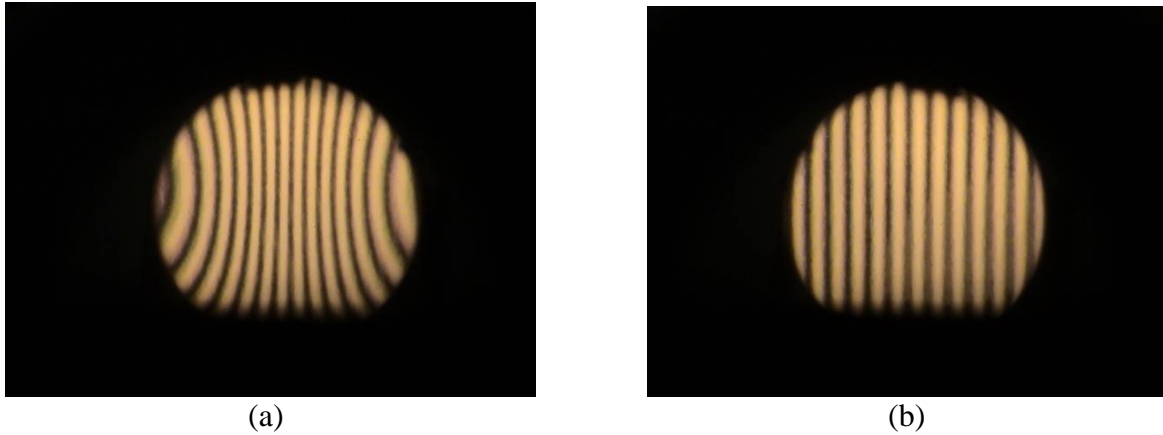


Figure 2. Comparison of tester lens positions: (a) Image showing the bowing of the lines caused by positioning the lens of the tester backwards in its holder and (b) an example of how the image should appear once all adjustments have been completed.

After alignment, the grating lines may appear elliptical, rather than the desired round shape, and the number of visible grating lines may differ from the preferred range of 12 to 14 lines. To correct the elliptical shape and increase the vertical height of the image, the height of the lens can be adjusted; this may require a change in the tilt of the mirror to redirect the light back to the eye position. To achieve an optimum number of visible lines, the distance between the focusing lens and optical tester also may require adjustment. Starting with the optical tester in a fixed position, the lens is moved to a point a few inches from the tester, resulting in a larger number of lines becoming visible. From here, the lens is moved towards the mirror until the desired 12 to 14 lines are present (figure 2b). Moving the lens further from the tester will result in a decreasing number of lines until the focal length of the lens is passed, at which point the number of lines will begin to increase again. The distance between the lens and mirror does not affect the number of lines; rather, it affects the quality of the visible grating lines. Finally, the placement of the sample between the lens and the mirror will not affect the distortion seen in the grating, but it will affect how visible the surface defects and details of a sample become.

The optical distortions seen through the Ann Arbor distortion tester are the result of changes in lens power (magnification) over the surface of the optical sample. One of the main results of a change in lens power is the change in the number of visible lines and the distance between them. A positive change in lens power will *decrease* the number of lines, *increasing* the space between them, while a negative change in lens power will *increase* the number of lines, *decreasing* the space between them. Figure 3 shows these changes in the line pattern due to a +0.125-diopter lens (figure 3a) and a -0.125-diopter lens (figure 3b). Optical standards have 0 diopters of lens power.

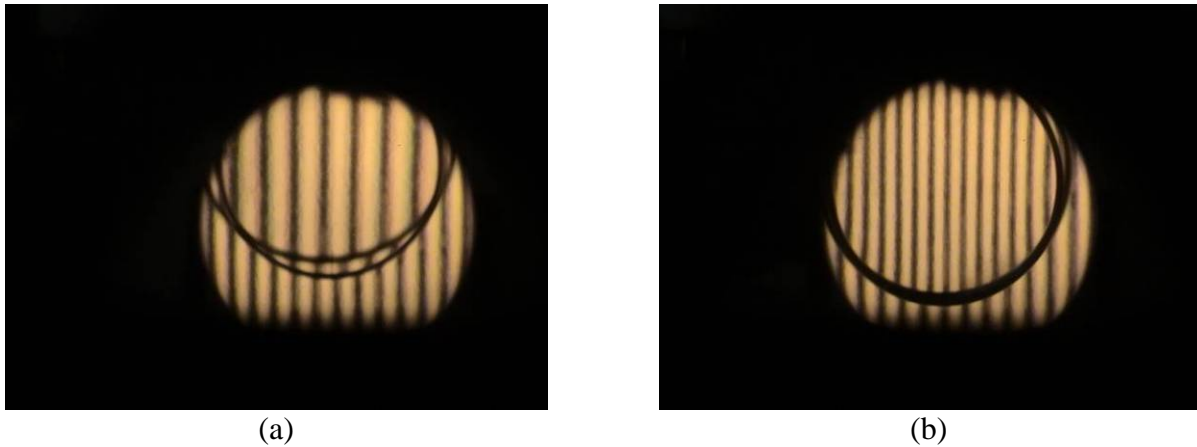


Figure 3. Effect of lens power on line number: images showing (a) the effects of a +0.125-diopter lens on a 13-line standard and (b) the effects of a -0.125-diopter lens on a 12-line standard.

Another important issue is that in order to properly evaluate the distortion present in an optical sample, the sample must be rotated through at least a 90-degree range. This is necessary because the Ann Arbor device can only test one meridian of distortion at a time, which is based on the orientation of the sample. As the sample is rotated, there likely will be variation in the distortions present (figure 4).

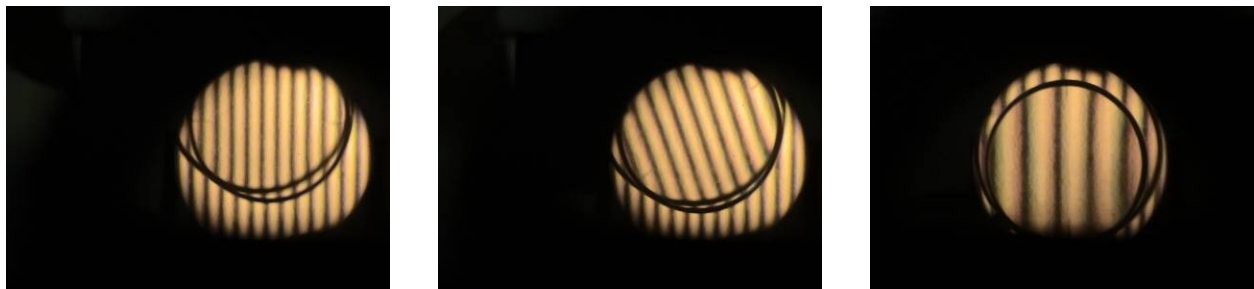


Figure 4. Effect of sample rotation on line and shear distortions: An example of a +0.25-diopter astigmatic lens sample with differing distortions at, from left to right, 0 (in line with the meridian of the tester), 45, and 90 degrees.

The current line distortion pass/fail criteria for a sample are based on two key distortion types: line deviation and shear patterns. For line deviation (e.g., a line curves, bends, or becomes slanted), the fail criteria threshold is if any line is deviating more than one line spacing such that it would touch an adjacent line if that line also had *not* been affected by the change in diopter value. A shear pattern occurs when a line is twisted, disrupted, or more misshapen than just a bend or curve; the fail criteria threshold for this type of distortion is any shear pattern having more than one-half line displacement. Figure 5 shows examples of a line deviation (figure 5a) and a shear pattern (figure 5b).

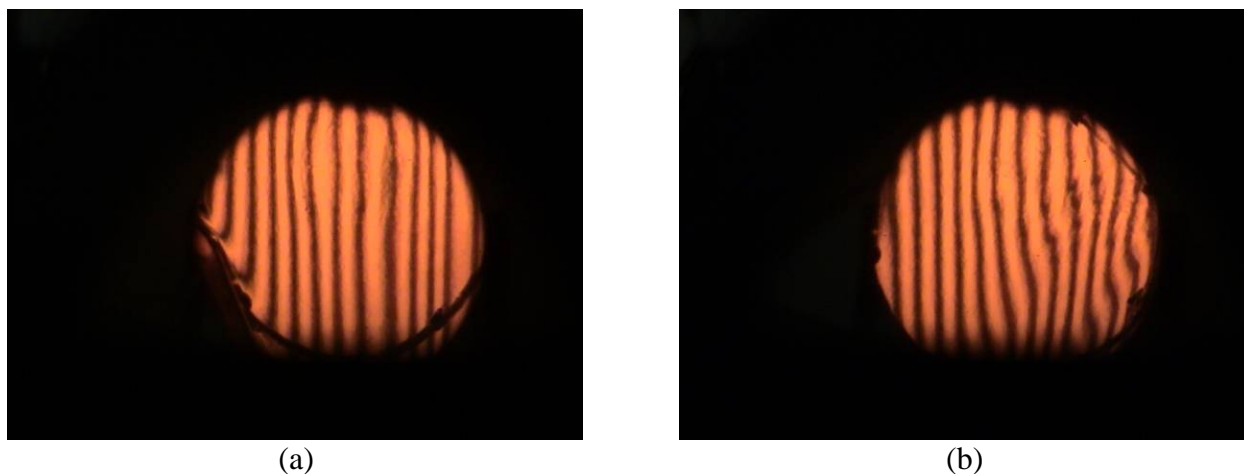


Figure 5. Line deviation and shear patterns: Images showing (a) an example of a line deviation for an amber tinted protective mask outsert and (b) an example of a shear pattern.

A common criticism of the Ann Arbor distortion test is that determined results of an evaluation can, and often do, vary based on the observer and their technique for using the device, i.e., the test is very subjective. It is quite possible for two evaluators to independently test the same optical sample on the same Ann Arbor device and arrive at different results regarding the quality of the sample. This is due to the results of the test being dependent on a subjective visual comparison to a set of known pass/fail images showing various intensities of line distortion and shear patterns (figure 6), as per MIL-V-43511D Detail Specification Visors, Flyer's Helmet, Polycarbonate, 12 Oct 2006². This means that results are very dependent on the user's observational skills and experience and are reported using subjective, *qualitative* details rather than objective, *quantitative* data. While it is theoretically possible to obtain quantitative results from this test, doing so is usually difficult and very time-consuming, and therefore rarely is attempted.

The purpose of this project was to develop an objective method for quickly and easily obtaining highly repeatable quantitative results that could be used to aid in determining the optical quality of a test sample. The proposed technique uses an image-capturing camera and image analysis software to compare the Ann Arbor distortion test image with a sample in place to a standard, zero-distortion test image and calculate an objective (quantitative) distortion value. The proposed technique utilizes MathWork's MATLAB[®],³ a high-level language and interactive environment for numerical computation, visualization, and programming, as the basis for the image analyses. MATLAB is a data analysis tool highly useful in image processing for test and measurement applications.

² It should be noted that these standards for pass/fail have been duplicated in Military Specification optical standards since the 1960s; one of the first uses in such a specification was MIL-L-38169 (USAF) 26 March 1963, Military Specification Lens, Goggle, and Visor, Helmet, Optical Characteristics, General Specification For.

³ MATLAB is a registered trademark of MathWorks, Inc., 3 Apple Hill Drive, Natick, MA 01760.

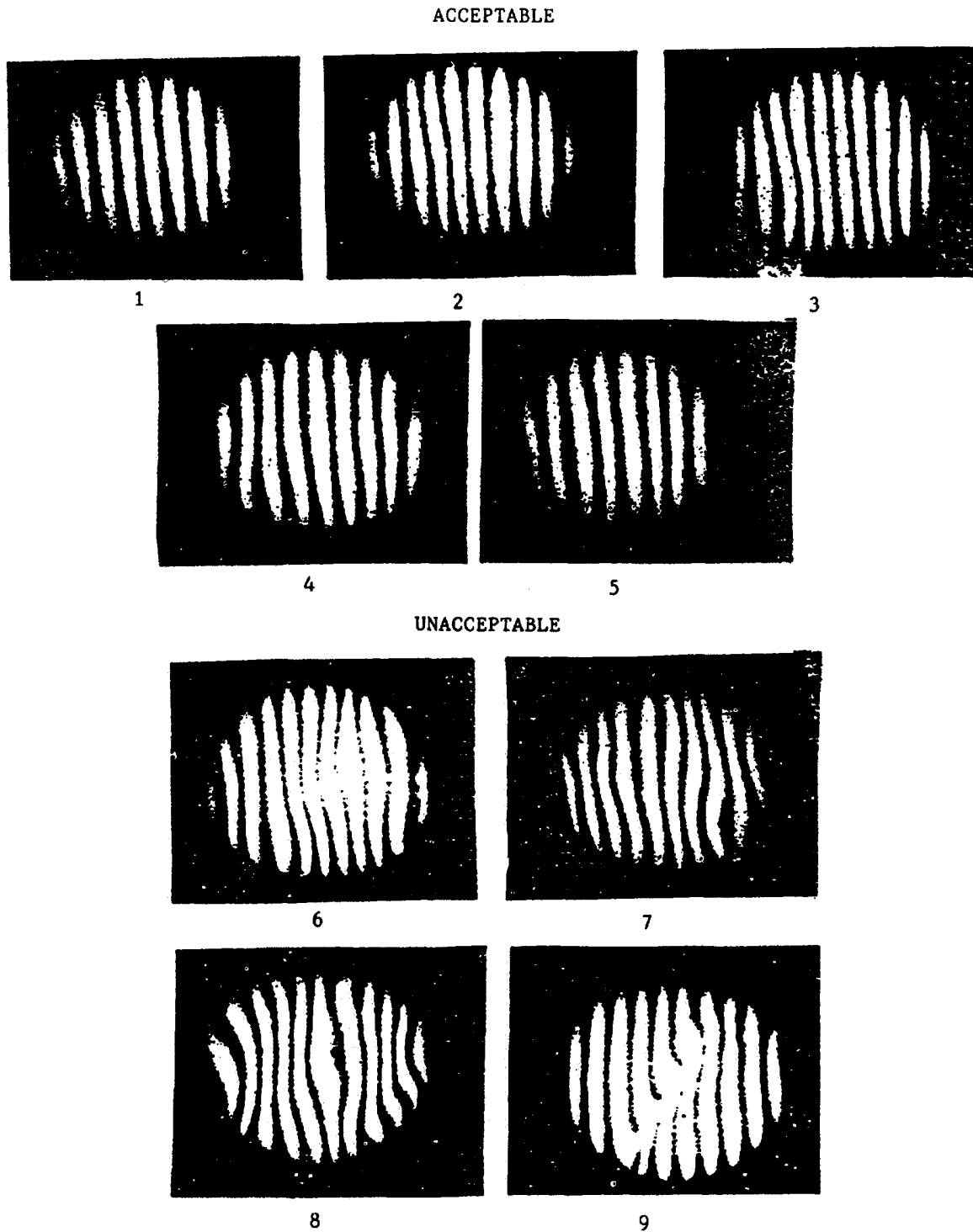


FIGURE 1. VISORS DISTORTION
STANDARDS

Figure 6. Pass/fail criteria images from MIL-V-43511D (labeled 'figure 1' in that document, as seen above) against which a result image from the distortion test is compared.

Method

The equipment used in this procedure includes: Ann Arbor distortion tester with 50-line grating reticule, IQeye 720 digital video camera with 12- to 40-mm lens, two Dell Optiplex 790 computers (one for the camera and one with MATLAB), and MATLAB Version 7.11.0.584 (R2010b) with Signal Processing Toolbox version 6.14 (R2010b).

The original goal of this project was to create a single, quantitative assessment that could be used to rate an optical sample as passing, failing, or borderline, requiring further examination. A result above a certain threshold value would be considered passing, while results below that value would be considered failing. However, it was quickly determined that this would be very difficult to achieve, as there are a large number of variables contributing to the subjective level of distortion in a sample. These variables include number of lines, extent of the curvature of the lines, distance between the lines, line thickness, line shear, and lens power. At first it was planned to use the MATLAB numerical computing environment to grade each of these variables individually and use multiple pass/fail scales to define a sample's quality, but it was eventually decided to focus on changes in number of lines, line distance, and especially lens power, which plays some part in all criteria used to define pass/fail. These variables were chosen because they were major indicators of distortion and major factors in determining a passing or failing sample. Other variables, such as line shear, play a much smaller role in determining quality and may be present in both passing and failing samples. Before any criteria could be measured, however, a method had to be developed to capture images of standards and various levels of distortion and import them into MATLAB.

In order to digitally capture images of the distortion in an optical sample, an IQeye 720 video camera with a 12- to 40-mm focal length lens was placed at the position of the eye shown in figure 1. (See figure 7 for a picture of the camera and its location in the distortion tester.) The components of the distortion tester then were repositioned to obtain the correct number of lines in the field-of-view, and the camera was focused to provide the sharpest image possible. The table below shows which option was chosen for each setting under the settings tab of the camera computer interface.

Settings for IQeye 720 camera.

Setting	Option
JPEG quality	'superfine'
Timestamp	'disabled'
Electronic shutter	'optimize quality'
Autogain speed	'locked'
Sharpness	'high'
Gain style	'clipaverage'
LIGHTGRABBER	'disabled'

Once the equipment was set up for optimum image quality, a standard image (i.e., an image with no optical sample) was captured and saved. This step was followed by capturing additional

sample images showing a range of distortions to be used as test images for any MATLAB codes that would be written. (Figure 8 shows a view of the computer interface window used for image capture.) Anytime a part of the distortion tester was repositioned, a new set of standard and sample images were captured and saved to a separate folder to ensure they were tested only against each other. New images also were taken anytime a property of the digital image was altered or if any change altering the position or number of lines in the standard occurred.

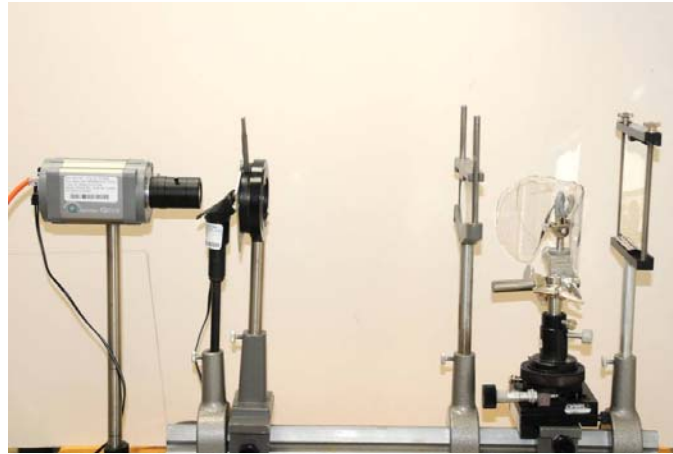


Figure 7. IQeye 720 video camera and Ann Arbor distortion tester.

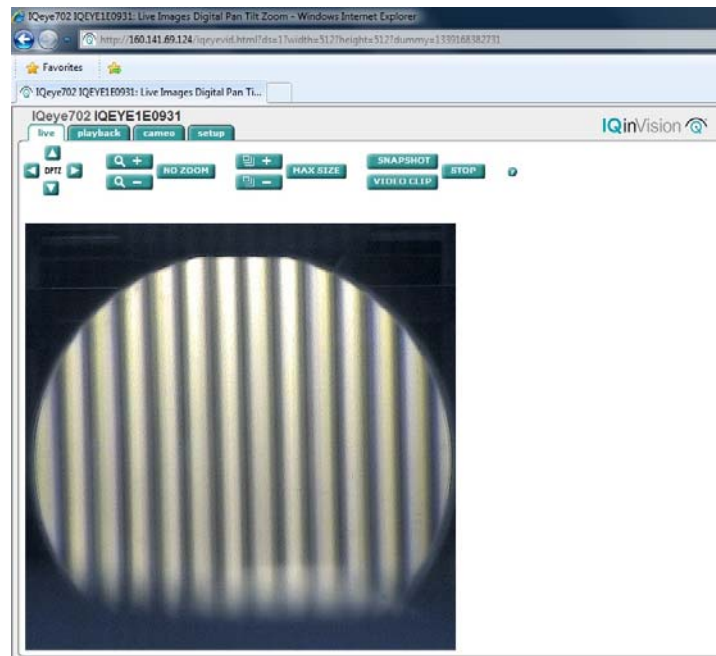


Figure 8. Computer interface for capturing images seen by IQeye 720 camera.

Once an image was captured, the next step was to import it into MATLAB, performed by choosing 'Import data' in the MATLAB Workspace. These data, from any image, were in the form of a large matrix, with two coordinates for the location of each pixel and three numbers at

each location for the red, green, and blue (RGB) values.⁴ The initial attempts at analyzing these data involved using a rough estimate of where the center of the distortion grating would be, compared to the whole image. From there, the code searched for the locations of two pixels in adjacent bright lines, but in the same pixel row, where all three RGB values were maximized. This was an attempt to determine a value for the distance between the two center lines. Due to all three RGB values often having their maximum values across an entire bright line, the location the code found for measurements was often at a transition point to or from a dark line, where the first or last location of maximum RGB values occurred. Next, a point with the maximum RGB values in one bright line was located on a pixel row near the center of the grating; then the corresponding maximum point 100 pixel rows up was located. The angle of a line between the points on these two rows was calculated using the change in horizontal pixel location of the maximum values between the two rows (figure 9).

Another MATLAB script attempted to measure the “curve” of the center line. This was done by comparing the change in horizontal positions of the points with the highest RGB values, on either side of the line, with the horizontal positions of the similar points in every other row in the distortion image. Alternate versions of these codes were written for horizontal gratings as well.

However, these codes had many issues. The size of the whole image and the center location of the distortion grating were not constant at this point, and using an estimate to determine the center via three maximized values was very inaccurate; it often led to the ‘center’ of the image being located near the top and/or side where the lightest part of the whole image, not the distortion grating, was located. Also, due to the code’s tendency to give a location at a transition point from dark to light lines or light to dark lines, it often counted two lines for every one bright line, despite the script setting a limit on how close to each other the values determined for these locations were allowed to be.

The angle-measuring script had a tendency to report very large angles due to differences in the total number of light lines between the two rows used. The script would measure the angle between one light line in one row and the neighboring light line in the other row (figure 9). Changes to the codes were made to let the code automatically account for these problems and adjust itself. These changes included reducing the distance between the points used for the angle, or changing the pixel row locations to center the measuring in the distortion grating. However, the first change usually resulted in a very small distance between the pixel rows used, sometimes as little as five pixels. These data, provided from such a distance, would not be useful for assessing quality. The second change was successful more often than the first. However, the code would often encounter the same issue regarding the center location of the image mentioned above, and end up calculating the angle between two different bright lines elsewhere on the

⁴ The camera used was in color, despite the images being nearly black-and-white, so MATLAB imported the RGB values from the images.

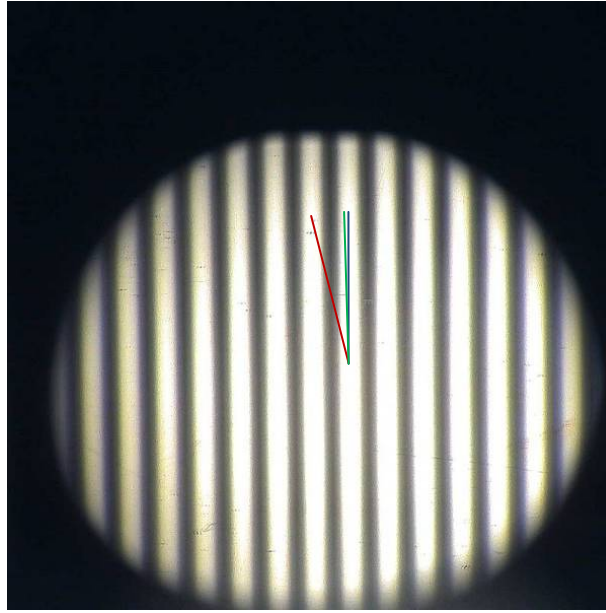


Figure 9. Example of line angle measurement error: Figure shows the issue often encountered with the script when attempting to measure the angle of a line. The blue line indicates perfectly straight vertical line used as a standard for comparison; the green line indicates the position data desired when attempting measure the angle of the bright line, while the red line shows an example of the incorrect position data often measured due to the different number of bright lines counted across the center and the top of the distortion grating.

image. This second change was also more image-specific than would be useful in an analysis tool meant to be used in an actual distortion test.

The images were fixed at a specific size of 512 by 512 pixels, and the distortion grating was increased in size to fill as much of the whole image as possible, putting the center of the distortion grating in the center of the image (figure 10). A 512 by 512 pixel size was chosen for three reasons: first, it was very close to the exact diameter of the distortion grating when the image was completely optimized in terms of brightness, alignment, and focus; second, a square matrix was easier to work with in MATLAB than a rectangular matrix; and third, the number 512 is a power of two, which makes many mathematical analysis methods (e.g., a Fourier transform) easier to perform. Another change was to convert the three RGB values into a single luminance value, as described below, to simplify both the analysis and the codes and to allow for manipulation of the matrix as needed. Finally, it was decided that for each light line only the location and value of the luminance at the absolute peak in the center of a line would be used. These changes led to an almost complete restart of the code writing, with only parts of previous scripts being carried into the new versions. This also led to the use of the Signal Processing Toolbox due to the shape of the luminance curves.

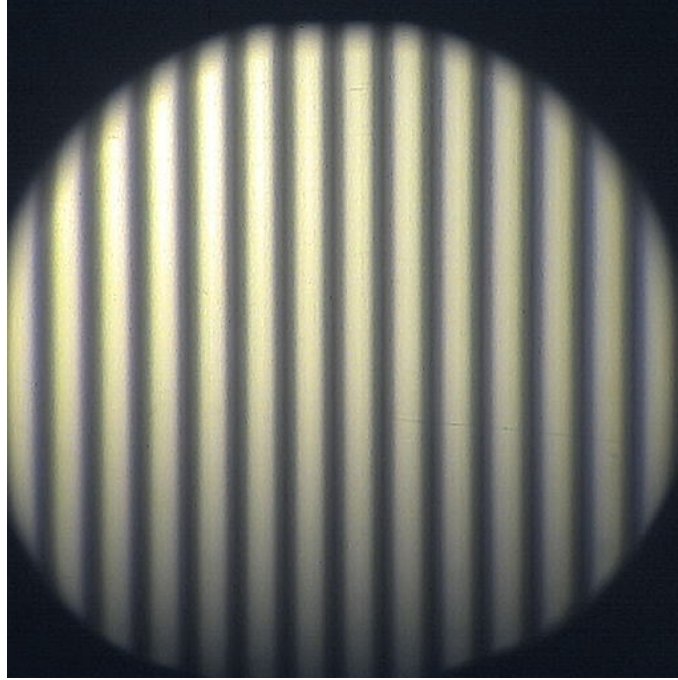


Figure 10. Optimal standard image, 512 by 512 pixels with the distortion grating filling as much of the image as possible.

The first step of every version of these scripts was to take the data from the imported images and convert them to a more manageable form for MATLAB. As stated earlier, the imported data came in the form of 512 by 512 by 3; that is, a 512 by 512 matrix with three values at each point for RGB levels. Using the equation below, the RGB values were used to create a 512 by 512 matrix where the value at each point was now a single, relative luminance value ranging from 0 to 255.

$$\text{relative luminance} = 0.2126 * R + 0.7152 * G + 0.0722 * B$$

When each row of data was plotted individually, the resulting shape was similar to a signal wave, except with large amounts of noise and large, flat peaks (i.e., the luminance peaking at 255 for many consecutive values). The next step was to smooth each row of the 512 by 512 data matrix by using three passes of a seven-value sliding-average technique, smoothing the end points as well. This was accomplished via a 'smoother' function also written in MATLAB. Three passes were required in order to remove all flat peaks from the data; originally both one and two passes were tried but there were problems in counting peaks as described later. Once this was completed these data were in the form of a 512 by 512 matrix of luminance values, with clearly defined troughs and peaks for each dark and light line on the image (figure 11).

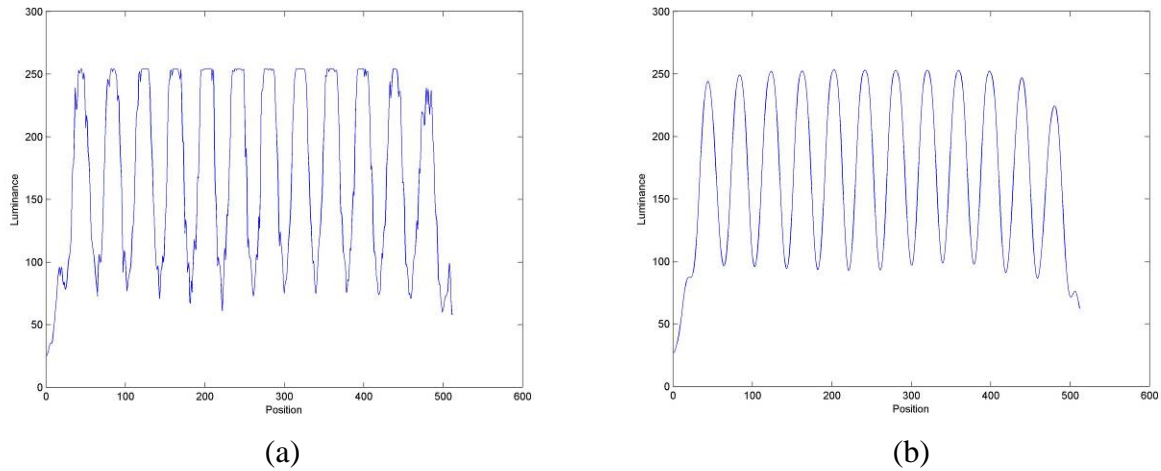


Figure 11. Plots of the luminance profiles across a standard image at row 256, (a) before and (b) after smoothing with a moving average.

The first attempt at analyzing these data was based on finding and counting the number of peaks above a certain value and measuring the distance between them in number of pixels of the image. This required setting a minimum luminance value for what could be considered as a peak (usually set to about 70 percent of the maximum luminance measured in the images and easily changeable if needed) and a minimum distance between two pixels that must occur before another peak could be counted (originally set to 30 pixels but adjusted as needed). The number of peaks, their locations, and the luminance value at each peak were found using the ‘findpeaks’ function included with Signal Processing Toolbox. This script also performed other tasks, including: finding the maximum and minimum distances between the peaks for every pixel row; counting the maximum number of peaks found across the image; and plotting the distance between peaks for the pixel row with the most peaks and for the rows with at the most 50 pixels above and below the row with the most peaks. (The value of 50 was allowed to self-decrease by the code in order to ensure the distance plots corresponded to the same bright lines along the upper- and lower-most rows plotted.) The script also plotted the luminance profiles of these three rows and marked the peaks, and gave some measure of how tilted the bright lines were by comparing the horizontal pixel locations of the peaks between the upper- and lower-most of the three rows (figure 12). Another script was written to provide the average angles of each line using the same procedure as with the original scripts described above, but the same issues as before were encountered. Versions of these scripts for horizontal grating pictures also were written.

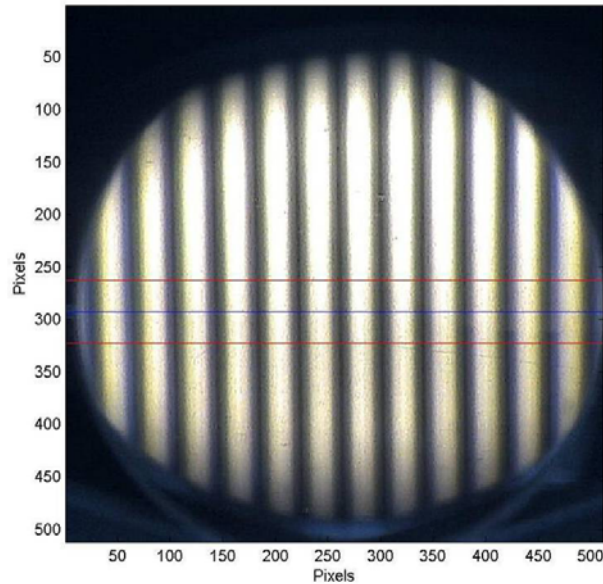


Figure 12. Example of standard image with three lines. The blue line shows where the most lines across the image were counted (pictured 13 lines), while the red lines are the rows used to measure the line tilts and angles for this specific image.

However, additional problems arose when these codes were implemented. One of the first problems encountered was in the number of peaks reported by the script. Originally these data were only smoothed once; however, due to the strength of the noise in the profile, some of the smoothed peaks had miniature troughs and dents along the sides and top, leading to multiple peaks being recorded when there was only one real peak. This led to using the three-pass version of smoothing mentioned previously. Another issue with the number of peaks reported was due to the need to set a minimum luminance value and minimum peak distance for use in the 'findpeaks' function (while the function runs without setting these limits, not doing so provided far worse results than when they were set). In images where there were many lines, as with minus power lenses, the minimum peak distance was too large and many peaks were skipped, whereas in the original data or data with one smoothing pass, a smaller minimum peak distance led to too many peaks reported. The minimum luminance value became a problem when using a tinted lens, as the value the script calculated to use would often be too high to correctly count peaks, and the luminance value also caused problems when set too low, catching noise and other data that should not be counted as peaks. Finally, one last problem was encountered with the location of the peaks being incorrectly measured, leading to distances being incorrectly calculated. After these data were smoothed three times, the peaks would be well defined but asymmetrical. This would cause the peak to be reported closer to the side than the center of the hump, which would increase or decrease the distance measured between neighboring peaks. This was compensated for with another MATLAB script that finds the locations of two nearly equal luminance values on either side of the peak and average them using this new location value as that of the peak. However, the other issues eventually caused a switch to looking at the locations of the troughs, rather than the peaks, as the troughs were symmetrical and better defined and did not require a minimum distance value. A new value, the minimum trough value, was created to prevent values below a certain point from being counted as troughs (currently set

at a luminance value of 57 but easily adjustable within the script). This was necessary to prevent coordinates outside the distortion grating image, or just inside the edges where the image quality is poorest and luminance values very low, from being counted as troughs. This value plays a far less important role than the minimum luminance value.

The final, implemented versions of the codes followed a similar procedure to the peak-finding code, but instead focused on finding the troughs (lowest points) along the luminance profiles. These represent the locations and luminances of the dark lines of the grating. These codes produced all of the same results as the peak scripts (number of lines [though now dark lines, not light], distances between them, etc.), and now showed the results of both a standard and a sample image simultaneously for easy comparison. New results calculated include: the averages, medians, and standard deviations of the distances between the lines for both the sample and standard images; a plot of the angles of the lines, calculated from the tilt previously measured, for both the sample and standard images; and a single plot showing both the minimum and maximum distances between troughs for every pixel row with more than one dark line for both the sample and standard images. Once thoroughly tested, these codes were used to count the number of lines present and the distances, in pixels, between them, of three reference sample lenses of known lens power (0, -0.25, and -0.50 diopter) with standards of 12, 13, and 14 lines. These data were used to derive the following equations for lens power between two lines in a sample based on the distance in pixels between them and the number of lines in the standard:

12-line standard	Power (diopters) = $\frac{-9.2632}{\text{distance}} + 0.2339$
13-line standard	Power (diopters) = $\frac{-10.4720}{\text{distance}} + 0.2653$
14-line standard	Power (diopters) = $\frac{-9.4423}{\text{distance}} + 0.2830$

These equations were incorporated into the MATLAB scripts and used to create both a line plot showing the lens power across the row of the distortion grating with the most lines, and a 3-dimensional surface plot showing the lens power over a wide area of the distortion grating, color-coded to indicate whether a portion of the surface falls in or out of a given range of values that indicate a passing or failing lens power (a ± 10 percent borderline region is indicated as well). If a certain percentage of the surface fails the lens power test (currently set to 10 percent of these data used to create the surface, but easily adjustable within the code), the whole lens is indicated as having failed the lens power test. The lens also can be indicated as borderline or passing based on similar criteria. This section of the code also creates a section in the results data files for the size of the surface plot, statistics of the diopter values (i.e., minimum, maximum, mean, median, and standard deviation), and which equation from above was used to calculate these based on the number of lines in the standard.

Testing of this new diopter/lens power test showed that while it was highly accurate at measuring lens power changes across the surface of a sample, this type of analysis alone would be insufficient to definitively pass or fail a sample; many obvious failures due to line curvature were passing because the lens power fell within the specified ranges. It was decided that another

test, one based on some measure of line curvature, would be needed for the images where lens power tests failed to correctly judge an image. The first approach was to calculate the areas bounded by two dark lines and the red lines used to calculate tilt and angle (see figure 12 for an image with red lines). The areas between each of the lines across the image would be plotted and compared to each other and the mean. However, this method proved to be inaccurate, as the area would depend on the position of the red lines that would self-adjust their position to ensure the tilts and angles were measured correctly. Also, areas where the type of distortion varied greatly, such as areas where two lines were very close at one point but very far at another, could measure as near or at the average area, which would be considered passing. At this point the method was deemed incorrect and new methods were considered.

After this, it was decided to investigate the distances between each line across every pixel row and the distance required for a line to deviate one linewidth. The distance required for a deviation of one linewidth was calculated by dividing the average width of the distortion grating in the whole image (about 495 of 512 pixels) by the number of lines in the image, then rounding half of this value up; since the image is made up of both light and dark lines, one linewidth would be from the center of a dark line to the center of a light line. This value was compared to the calculated differences between the minimum and maximum distances between dark lines for every pixel row of the image with more than one dark line between row 125 and an endpoint that self-adjusts based on the size of the of the minimum and maximum data sets (if neither of these affect the endpoint, the default is row 420). If more than 5.0 percent of the differences exceed the one linewidth distance value, the image fails (this was done to compensate for unusual distance measurements due to any markings or scratching on the sample that would affect the measured position of a dark line); if between 5.0 percent and 2.5 percent exceed it, the image is borderline; less than 2.5 percent exceeding values is a passing image. The plot of the minimum and maximum distances between the troughs was modified to include a plot of the average value between troughs, based on the method above; half of the plotted value would be the distance that must be exceeded to count as a failing value.

Finally, an interface with push buttons and editable text, run via an executable file, was created to automatically run these scripts upon selection of the images to be used and the range of acceptable lens power, and the resulting data and plots were labeled and described for easy analysis. The executable file was created such that no MATLAB experience is needed to use this analysis method.

Results

The final result was a graphical user interface (GUI), run via an executable file, that provided a way to: select the images to be used as the standard and the sample; define the range of passing lens power values; and select the location to save the results files and images (figure 13). Upon clicking 'Run,' the trough codes described in the final sections of the Methods section run in the background, and a total of 13 image files and two text files are created and saved in the selected file (four of the images are displayed automatically with a text file containing the main results for judging the sample, and a message indicating that all the files have successfully saved). Error messages will open if no standard or sample image are selected, or if no save file

is selected. This section will include descriptions and figures for each of the files and images saved, starting with the text files.

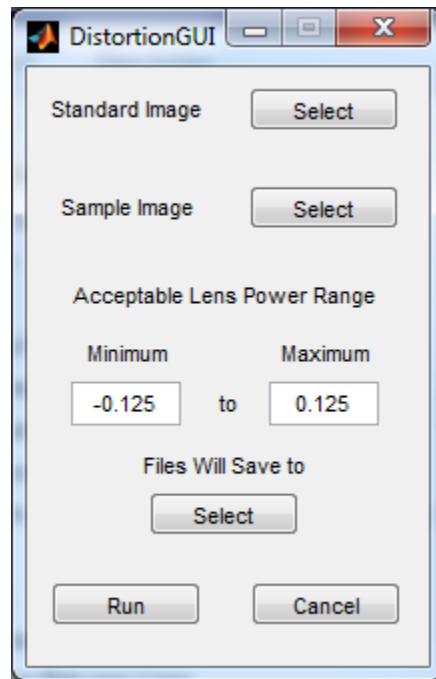


Figure 13. Distortion GUI window, used to select the images to be analyzed, the pass/fail lens power range, and file save location.

The two text files created are titled 'Main Results File' and 'Secondary File.' The 'Main Results File' contains data on lens power and the lens power related images, including: the position and size of the 3-dimensional surface plot on the distortion grating image; the minimum, maximum, mean, median, and standard deviation of the lens power values; the equation used to calculate lens power, based on the number of lines in the standard; and an indication of whether or not the optical sample failed the lens power test, determined by how many of these data values on the surface fell outside the passing and borderline ranges. (Note: To compensate for measurement errors and markings on the sample, at least 10 percent of these data values for the surface plot must fall outside the range specified on the GUI for the optical sample to fail the test). This file also contains information on the troughs for both the standard and sample images, including: the maximum number of lines counted and the pixel row where that count occurred; and the maximum, minimum, mean, median, and standard deviation of the distances between the dark lines. The results of the line distance test described in the methods are shown in this file. These results are: a) the size of the deviation required for a failure (with the maximum deviation measured), b) an indication of about how many failing values were counted before the code made the pass/fail decision, and c) a pass, fail, or borderline grade for the image. The 'Main Results File' opens upon running the GUI. The 'Secondary File' contains the pixel row locations of the lines seen on the various standard and sample images, specifically the red and blue lines, and gives the distances between them in number of pixels. It also contains simplified versions of the descriptions of the 13 images that will be given below.

There are a total of 13 images created when 'Run' is selected in the GUI: Diopter Change Blue Line, Diopter Change Surface, Sample Three Lines, Sample Distances Between Lines, Sample Green Lines, Sample Line Tilt and Angle, Sample Luminance Troughs, Sample Minimum and Maximum Distances by Pixel Row, Standard Three Lines, Standard Distances Between Lines, Standard Line Tilt and Angle, Standard Luminance Troughs, and Standard Minimum and Maximum Distances by Pixel Row. Four of these open when the GUI finishes running and are identified in their descriptions below. All the images shown below were created using the same standard and sample image.

- Diopter Change Blue Line: This graph (an example can be seen in figure 14) shows the change in lens power across the sample image along the blue line. The x-axis (Position) indicates between which two dark lines the change occurs. For example, a position value of "5" indicates the change occurs at the fifth pair of lines, lines five and six.

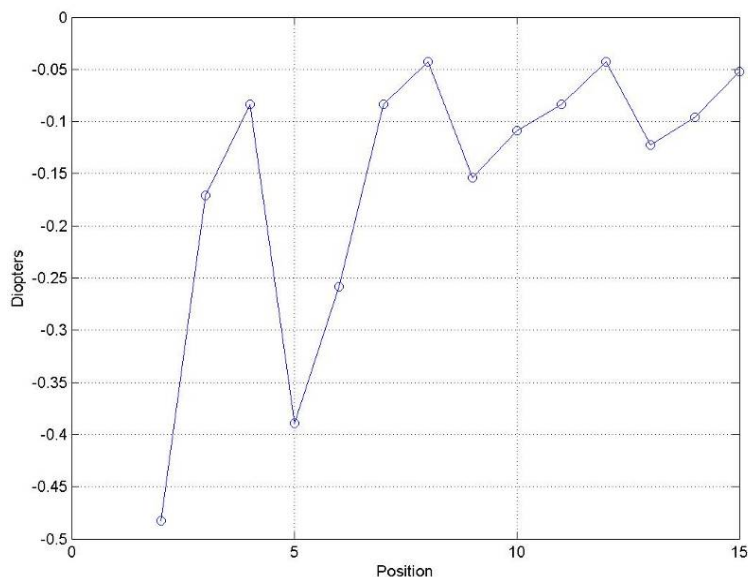


Figure 14. Example of the 'Diopter Change Blue Line' plot.

- Diopter Change Surface: This figure shows the change in lens power across the image over the area between the green lines seen in the image titled 'Sample Green Lines'. The x-axis (Position) indicates between which two dark lines the change in lens power occurs. For example, the position value of "4" indicates the change occurs between the fourth pair of lines, lines four and five. The image is color-coded, based on whether a portion of the image passes or fails: red is fail, yellow is borderline, and green is pass. This is one of the images that open upon running the GUI and appears in a window labeled 'Figure 8'; the version saved to the selected file cannot be rotated and is labeled 'Diopter Change Surface.' The version that opens when running the GUI can be rotated by first clicking on the 'Rotation' button (highlighted by a red box in figure 15 below) and then clicking and dragging the image itself. Figure 16 shows the same surface after rotation to -61 azimuth, 70 elevation.

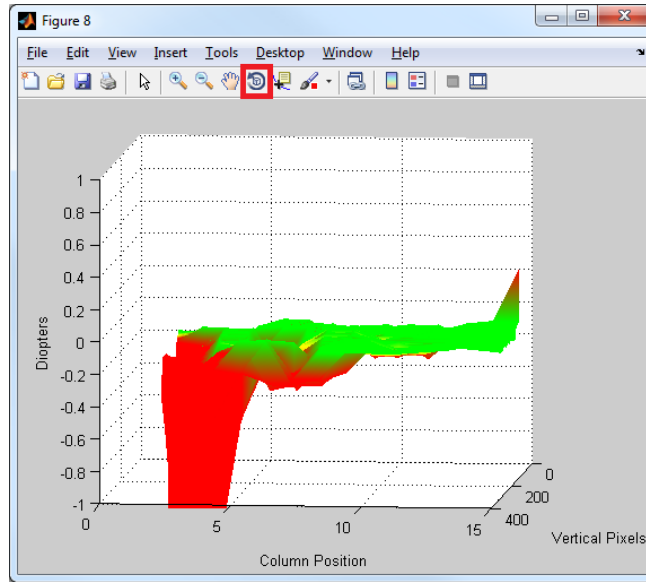


Figure 15. Example of the rotatable version of ‘Diopter Change Surface’ that opens upon running the GUI. The default rotation position is 6 azimuth, 8 elevation. Rotation is initiated via the button highlighted by the red box.

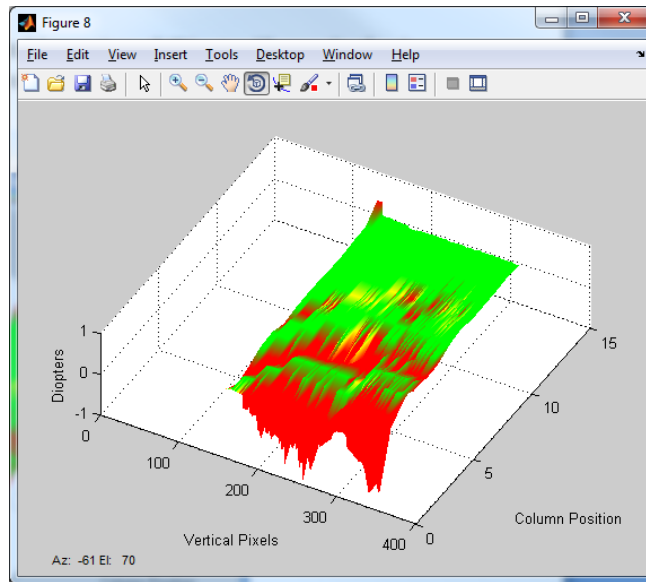


Figure 16. Example of the rotatable version of ‘Diopter Change Surface’ (for image shown in figure 15) rotated to -61 azimuth, 70 elevation.

- **Sample Three Lines:** This image (figure 17) shows the sample with the two red lines located at the rows used to measure line tilt and angle, and a blue line indicating one of the rows where the maximum number of troughs was counted.

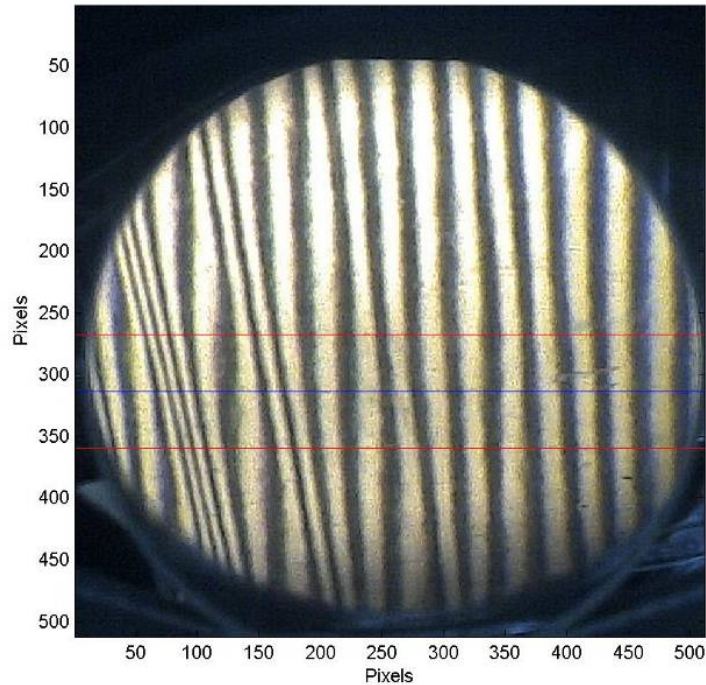


Figure 17. Example of the ‘Sample Three Lines’ image. The far right line blurs into the edge of the image in the row with the bottom red line, so no trough is counted at that position on either red line. A similar situation occurs with the far left line and the top red line. This leads to two less troughs counted along the red lines than are on the blue line.

- **Sample Distances Between Lines:** This figure (figure 18) shows, from top to bottom, the distance, in pixels, between the dark lines along the top red line, the blue line, and the bottom red line. The x-axis (Position) indicates between which two dark lines the distance occurs. For example, position value of "2" indicates the distance is between the second pair of lines (counting left to right), lines two and three. In order to prevent incorrect failures of the script due to both unusual distortions at the edge of the image and mismatching of lines between red lines, the first and last 15 pixels are ignored in counting troughs, which sometimes leads to one less distance plotted than there would be without the edging.

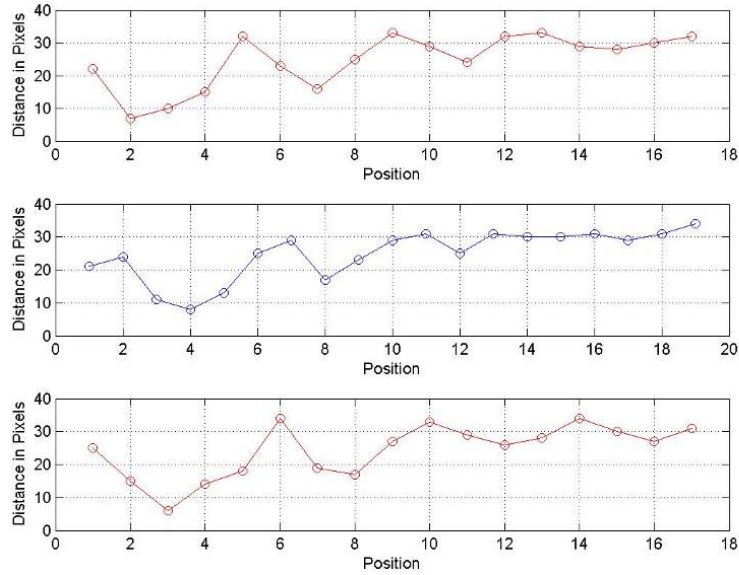


Figure 18. Example of the ‘Sample Distances Between Lines’ results.

- **Sample Green Lines:** This image (figure 19) shows the sample image with two green lines, which indicate the area over which the change in lens power is shown in the image ‘Diopter Change Surface,’ and one blue line marking a row with the maximum number of dark lines. This is an image that opens upon running the GUI in a window labeled as ‘Figure 6,’ while the saved version (seen below) is titled ‘Sample Green Lines.’

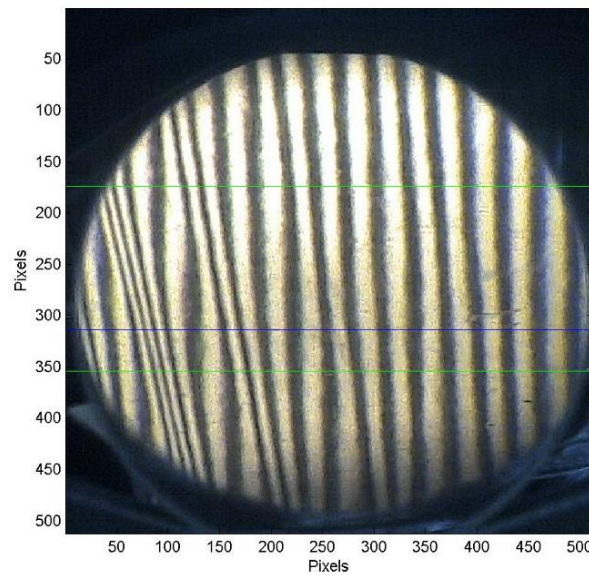


Figure 19. Example of the ‘Sample Green Lines’ image.

- **Sample Line Tilt and Angle:** The top plot of this figure (figure 20) shows the difference in horizontal pixel location of a trough from its location on the bottom red line to its location on the top red line (figure 17). A positive value indicates the line leans to the

left, while a negative value indicates a lean to the right. The lower plot shows the angle, in degrees, of each line between the two red lines.

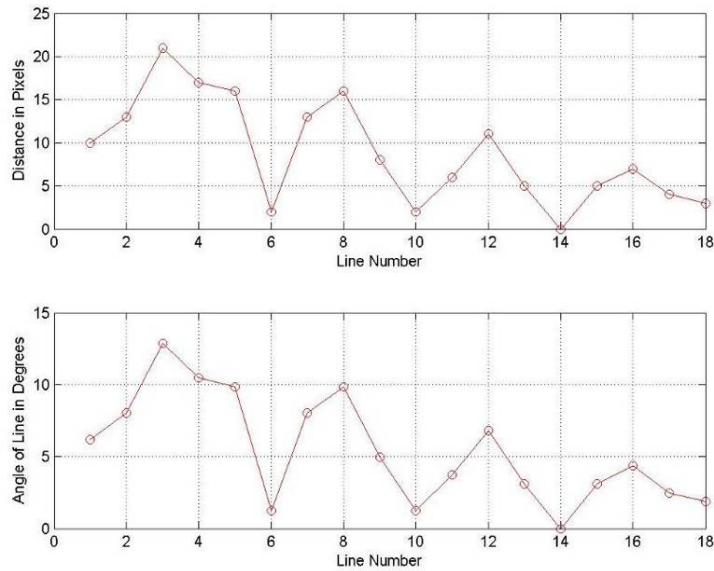


Figure 20. Example of the ‘Sample Line Tilt and Angle’ plots. Angles measured in degrees.

- **Sample Luminance Troughs:** This figure (figure 21) shows, from top to bottom, the luminance values of the sample across the top red line, the blue line, and the bottom red line. The troughs are marked and indicate the location of center of the dark lines.

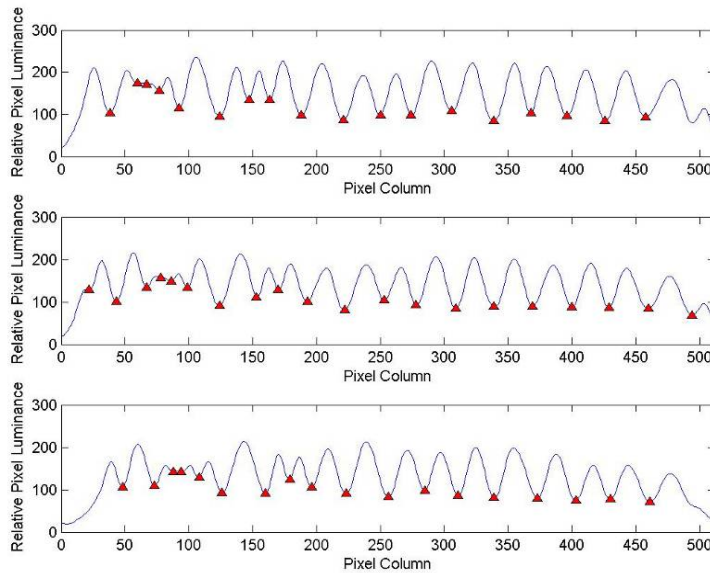


Figure 21. Example of the ‘Sample Luminance Troughs’ plots.

- **Sample Minimum and Maximum Distances by Pixel Row:** This graph (figure 22) shows the maximum and minimum distances between the troughs for every pixel row for which

there was more than one trough. The maximum distances are plotted in red, the minimum distances in blue, and the average distance, based on image width and number of lines, in black. This is one of the images that open upon running the GUI, in a window labeled as ‘figure 4,’ while the saved version (seen below) is titled ‘Sample Minimum and Maximum Distances by Pixel Row.’

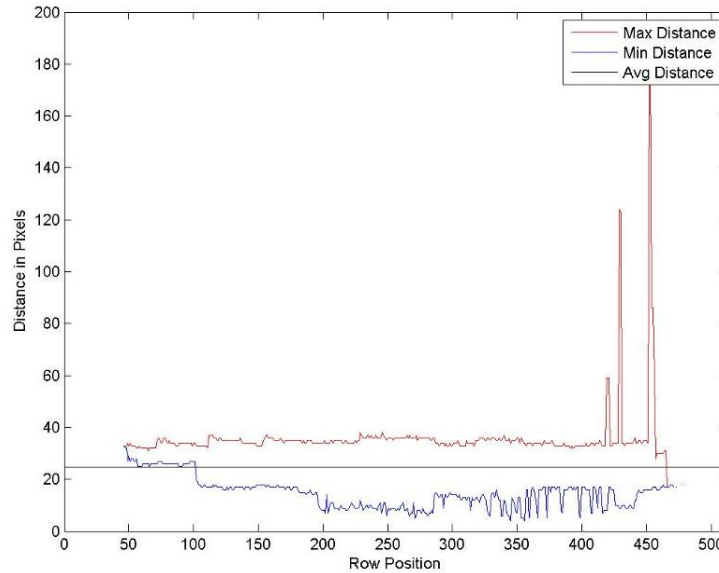


Figure 22. Example of the ‘Sample Minimum and Maximum Distances by Pixel Row’ graph. Note that the label of the x-axis is row position, not column position, so moving from left to right along this plot is equivalent to moving from top to bottom of the distortion sample image. Therefore, in this plot the large jumps in value seen on the right are due to the quality of the image near the bottom of the distortion grating.

- **Standard Three Lines:** This image (figure 23) shows the standard with the two red lines located at the rows used to measure line tilt and angle, and a blue line indicating a row where the maximum number of dark lines was counted. This is one of the images that open upon running the GUI, in a window labeled as ‘figure 9,’ while the saved version (seen below) is titled ‘Standard Three Lines.’

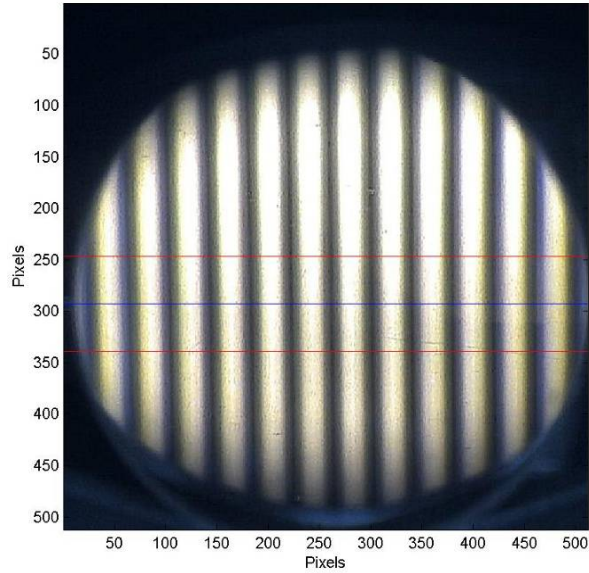


Figure 23. Example of the ‘Standard Three Lines’ image.

- **Standard Distances Between Lines:** This figure (figure 24) shows, from top to bottom, the distance, in pixels, between the dark lines along the top red line, the blue line, and the bottom red line. The x-axis (Position) indicates between which two dark lines the distance occurs. For example, a position value of “3” indicates the distance is between the third pair of lines, lines three and four.

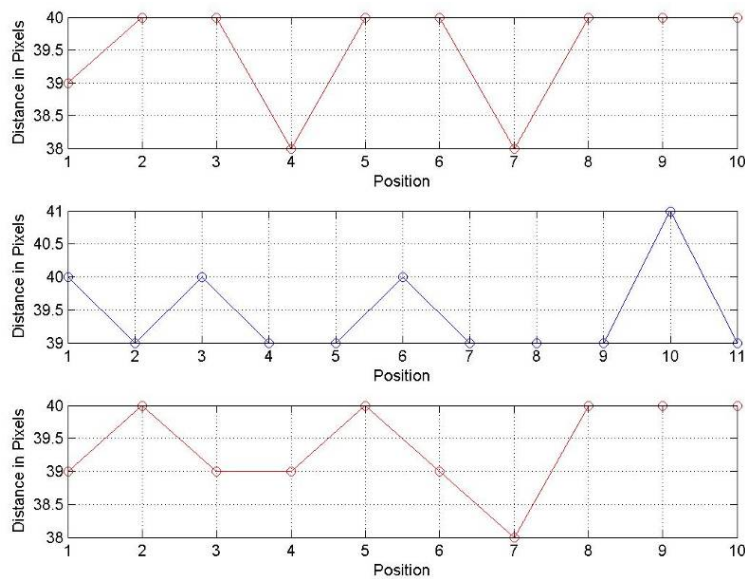


Figure 24. Example of the ‘Standard Distances Between Lines’ plots.

- **Standard Line Tilt and Angle:** The top graph in this figure (figure 25) shows the difference in horizontal pixel location of a trough from its location on the bottom red line to its location on the top red line. A positive value indicates the line leans to the left,

while a negative value indicates a lean to the right. The lower graph shows the angle, in degrees, of each line between the two red lines.

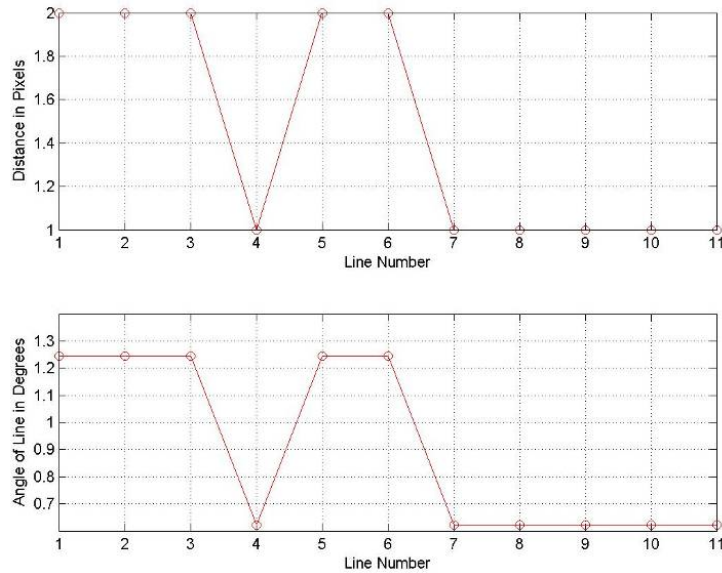


Figure 25. Example of the ‘Standard Line Tilt and Angle’ figure.

- **Standard Luminance Troughs:** This figure (figure 26) shows, from top to bottom, the luminance values of the standard across the top red line, the blue line, and the bottom red line. The troughs are marked and indicate the location of the center of the dark lines.

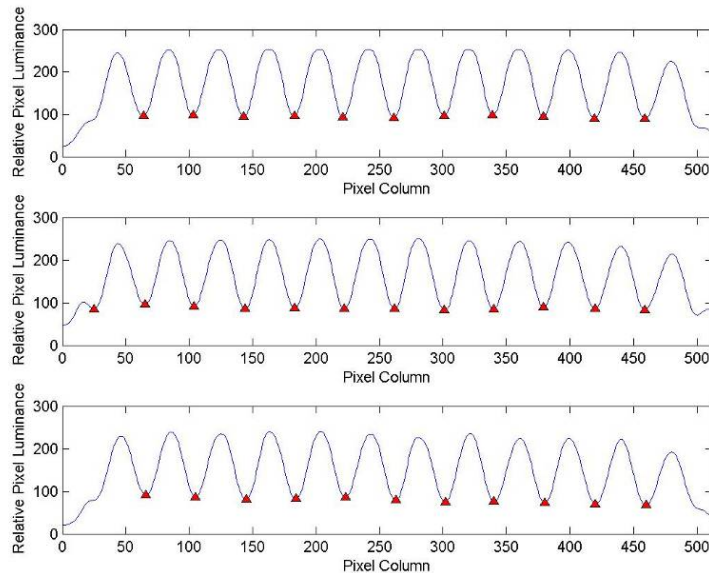


Figure 26. Example of the ‘Standard Luminance Troughs’ plots.

- **Standard Minimum and Maximum Distances by Pixel Row:** This graph (figure 27) shows the maximum and minimum distances between the dark lines for every pixel row

for which there was more than one trough. The maximum distances are plotted in red, the minimum distances in blue, and the average distance, based on image width and number of lines, in black.

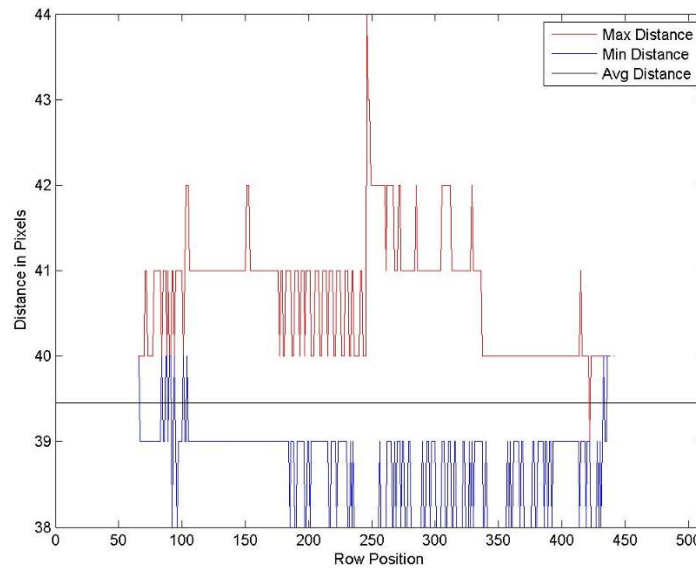


Figure 27. Example of the ‘Standard Minimum and Maximum Distances by Pixel Row’ graph.

Discussion

While adding objectivity to the evaluation of distortion in optical materials, this test cannot be used as a definitive pass/fail of an optical sample without being paired with user observation and discretion; it is intended to augment the analysis process, not replace it entirely. This proposed tool may provide clear data on the effects of a sample on line number, line distance, lens power, and other distortion qualities, but the final decision on the quality of an optical sample is at the tester’s discretion. The Ann Arbor distortion test itself is still very much a subjective, qualitative test, so there will always be limitations and problems with attempts to automate the process using computers and to define definitive pass/fail criteria.

There are some limitations to both the MATLAB analysis scripts and the actual Ann Arbor distortion tester and camera setup itself. First, the analysis code is very sensitive to abnormalities in the images used. If there are any markings on, or disruptions in, the optical sample, such as an outline around the critical area, an indicator of a problem spot, or even a finger or sample edge visible, this will reduce the calculated luminance of those pixels in the image, which may cause that row to be reported as the pixel row with the most dark lines (troughs), thereby over-counting the actual number of lines in the image. This same error also can occur when the optical sample is dusty, dirty, scratched, smudged, etc. Any defect in the quality of the optical sample may compromise the luminance measured at those pixels and cause this error. Ensuring that the test sample is as clean and free of markings and damage as possible before testing will reduce the likelihood of this problem, as would positioning the sample such

that no edges or fingers are in the image, but there will be times where a sample may be too small or too defective to be analyzed with this program.

Irregularities in the luminance of the image itself may cause problems when analyzing the images. A heavy tint on the optical sample may lower the overall luminance levels too much for the MATLAB script to compensate for, preventing an accurate analysis. Increasing the brightness of the light source or testing environment, or increasing the amount of light the camera collects will not help correct this problem. There will be samples too tinted for the analysis program to be used. The edges of the distortion grating image also pose problems for the scripts, especially if that is the location of the worst distortion; however, the code has been designed to compensate for this by focusing on a large rectangular area in the center of the distortion grating. This has been found to be where the greatest distortion is most likely to be placed by a user.

Misalignment of some of the components of the distortion tester apparatus, such as the camera, light source, or mirror, could reduce the luminance of a portion of the distortion grating image, reducing analysis to only a certain part of the image. Also, a very light background around the distortion grating section of the image, or a reflection of light from the distortion tester or external light sources directly into the camera, may greatly brighten areas of the image that would otherwise be dark; this too can interfere with analysis and lead to a miscount in the number of lines in the image. However, these issues (e.g., apparatus misalignment, overly bright background, and reflections) can be reduced or fixed completely simply by reducing the background light in the environment (e.g., dimming/turning off room lights) and realigning the various components such that the illumination is more consistent over the whole image. See figure 28 for examples of images with and without these problems.

However, despite these issues, this code is still a very useful tool in judging whether or not an optical sample passes the Ann Arbor distortion test. It can count the total number of lines much faster than an observer can, especially when there is a large amount of negative lens power and there are many lines close together. And, it provides not only the value of the lens power present over a large area of the image, but can be used to quickly locate areas with the greatest difference from the standard for further analysis with other equipment (such as a hazemeter or lensmeter). As well, use of both the lens power test and the line distance test has been very accurate in determining whether an image should pass or fail a qualitative test. Thirty-six images were evaluated using both the lens power and line distance test, and the results were compared to the pass/fail grade of a subject-matter expert. The criteria was that an image judged by the expert to be a passing sample must pass both the lens power and line distance tests to pass with the quantitative method; failure in either or both tests would lead to a failing result for the sample, while borderline results would count towards the results of the other test.

Of the 36 images evaluated using the quantitative MATLAB method, 31 (86%) matched an expert's qualitative determination of optical quality. Of the five (14%) evaluations that did not match the expert's results, four of the method's failures were for images that passed the lens

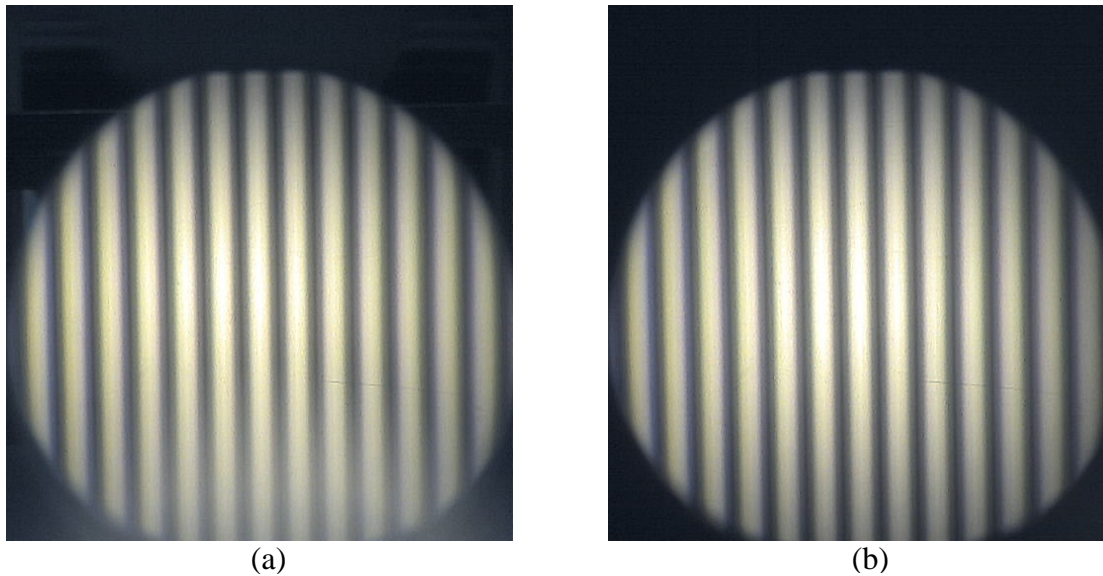


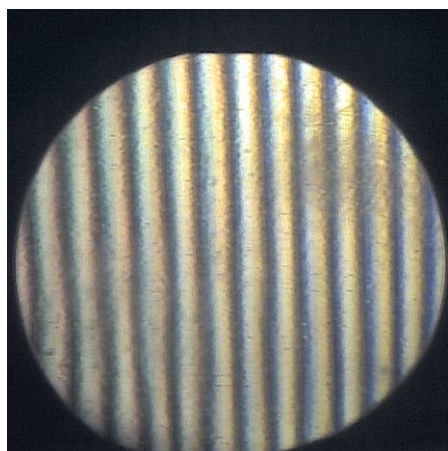
Figure 28. Non-optimal and optimal image comparison: (a) a standard image with both a bright, visible background around the edges (seen best in the top left portion) and a reflection along the bottom center edge (washing out the image) that can interfere with the MATLAB code's ability to count the number of dark lines and (b) the same standard image with those issues corrected by turning off the lights in the external environment and slightly repositioning the distortion tester light source and grating so that reflections are not directed into the camera.

power test but failed the line distance test and one was for an image that passed both the lens power and the line distance tests. These images are provided in figure 29.

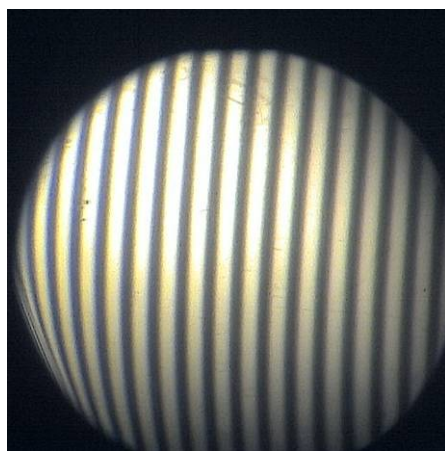
The distortion tester image in figure 29a should have passed the evaluation, but failed the line distance test of the code. Examination of the image and result plots showed many pixel rows where the minimum distance between dark lines was measured incorrectly as very small, most likely due to the many scratches and disfigurements of the test visor that can be seen in the image.

The image in figure 29b also should have passed, but failed the line distance test. The distortion of the dark lines along the bottom left edge caused many of the rows to have very small minimum distances between lines, causing the calculated differences of those rows to exceed the one linewidth distance.

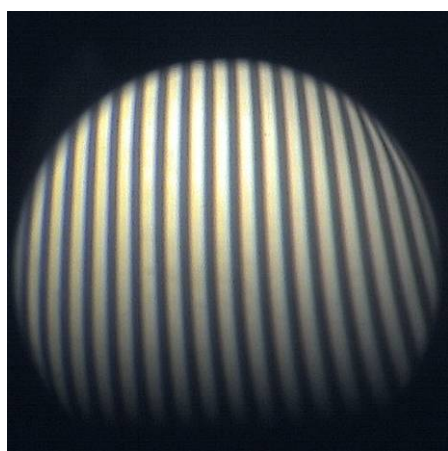
The image in figure 29c was one deemed unacceptable by the expert but which the MATLAB code determined to be acceptable. The test range for lens power was -0.125 to $+0.125$ diopter, while the code measured a mean of -0.11 diopter and a median of -0.10 diopter; only along the very edges did the code read outside the pass/fail range. For the line distance test, the linewidth distance (fail distance) was 15 pixels, and the maximum value measured by the codes was 11 pixels.



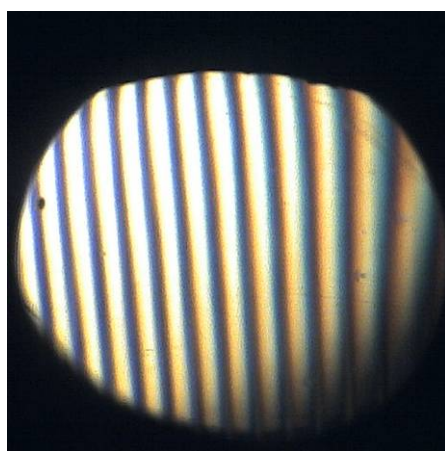
(a)



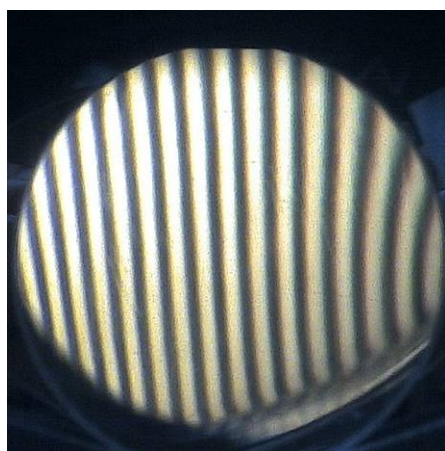
(b)



(c)



(d)



(e)

Figure 29. Images where the results of the MATLAB evaluation results did not match those of the expert user.

The image in figure 29d was a borderline pass image for the expert, but the software failed the image for the line distance test. The area where it failed can be seen on the far right of the image where the top of the image has very wide bright lines; here the bright areas are wider than one linewidth for much of the image, resulting in the failure. Due to this failure determination, the code discontinues its analysis of the remainder of the image (where the image improves in quality and would be determined acceptable).

Lastly, the image in figure 29e was a passing image that failed the line distance test. The reason for failure were the same as for the image in figure 29b, excessive distortion along the bottom edge, but only here on the right side. These results show that, while this proposed analysis tool cannot replace the users' personal judgments, it does provide meaningful, quantitative data that can augment an observer's judgment and lead to greater consistency between users' final results.

Conclusion

Quantifying the Ann Arbor distortion test has been a goal for many years, but only with some of the more recent advances in imaging technology and numerical analysis has the likelihood of achieving this goal increased. Through the use of the numerical computational program MATLAB, a method to quantify some of the results (specifically number of lines, distance between lines, line tilt, line angle, and lens power) has been developed and tested on a variety of images and found to be accurate in a large number of cases. All of the MATLAB functions employed in the described approach are provided in the most basic version of MATLAB. With more advanced MATLAB toolboxes, such as Image Processing Toolbox, or even more advanced software and/or image analysis kits, it may be possible to create ways to automate the entire test and analyze all the necessary qualities to give a definitive pass/fail grade. Modifications to the images themselves, such as conversion to grayscale or black-and-white to reduce issues caused by color or luminance variations, could improve analysis and results. Further improvements also could be made by better including expert knowledge on the use of the Ann Arbor device and distortion evaluations. This software is based entirely on the luminance data acquired from the captured images and does not incorporate the full experience of human researchers. With the assistance of an expert in distortion testing, enhanced codes could be created to improve overall performance.

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Appendix.

Standard Operating Procedure of MATLAB Image Comparison and Analysis Tool for Ann Arbor Distortion Tester

Standard Operating Procedure for Camera System and Image Analysis Software for Ann Arbor Distortion Tester

Contents

1. Introduction/System Description
2. System Components
3. Set Up
4. Use
5. Shut Down
6. Analysis

1. Introduction

The purpose of this document is to walk a user through the procedure for setting up and using the Ann Arbor Distortion Tester with IQeye 702 camera. This equipment is used to test the distortion of the external view caused by a test lens or display. This is done by viewing a set of grid lines and comparing the amount of distortion caused by the lens or display to a non-distorted standard. The various components of the system, and the software for storing the photos, will be discussed, followed by step-by-step procedures for set up, use, and shut down. The use of the DistortionGUI for analysis will be described in the last section.

2. System Components

This section will describe the various components of the Ann Arbor distortion tester and the camera menus.

A. Physical Components

There are six major components to the distortion tester: the camera, the light source of the optical tester, the grating of the optical tester, the lens of the distortion tester, the support for holding and positioning the optical sample, and the flat, front-surface mirror of the distortion tester. The last five are all mounted on a single stand; the camera is mounted to the table (see Figure 1).

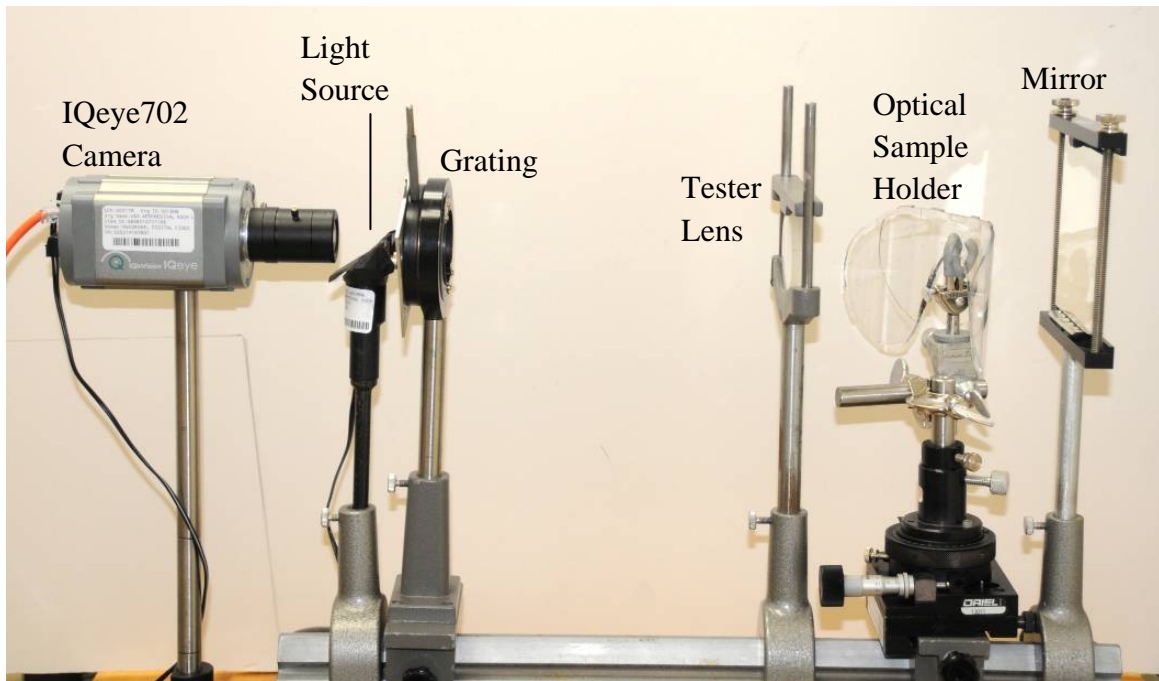


Figure 1. Ann Arbor Distortion Tester

- i. Camera
The camera used to capture the distortion images is an IQeye702 with a 12-mm – 40-mm lens. The connectors on the back are, clockwise from top left: power input, Ethernet connection, trigger connection, and video out. There is also a slot for a Compact Flash (CF) card below these connectors. On the lens of the camera are three knobs or wheels, two of which have handles: the large outer ring with a handle controls the zoom, the middle ring with no handle controls the aperture size, and the inner ring with a handle controls the focus.
- ii. Light source of optical tester
Light source for tester.
- iii. Grating of optical tester
Optical grating consisting of 50 lines. The handle on the side can be used to turn the grating to any angle desired.
- iv. Lens of distortion tester
A 182-mm focal length, 50-mm diameter lens.
- v. Support for test lens/optical media sample
The optical sample is held in place by the optical mount seen above. This apparatus allows for positioning of the sample in all orientations, as well as a simulation of rotation about an eyeball. This piece is not necessary for image taking and analysis, but can make it easier to use the camera by holding the

sample in place. It can be removed and replaced easily and without interfering with the operation of the tester.

vi. Mirror of distortion tester

Front-surface mirror positioned to reflect the light from the optical tester back to the camera.

B. IQeye702 Camera Menus

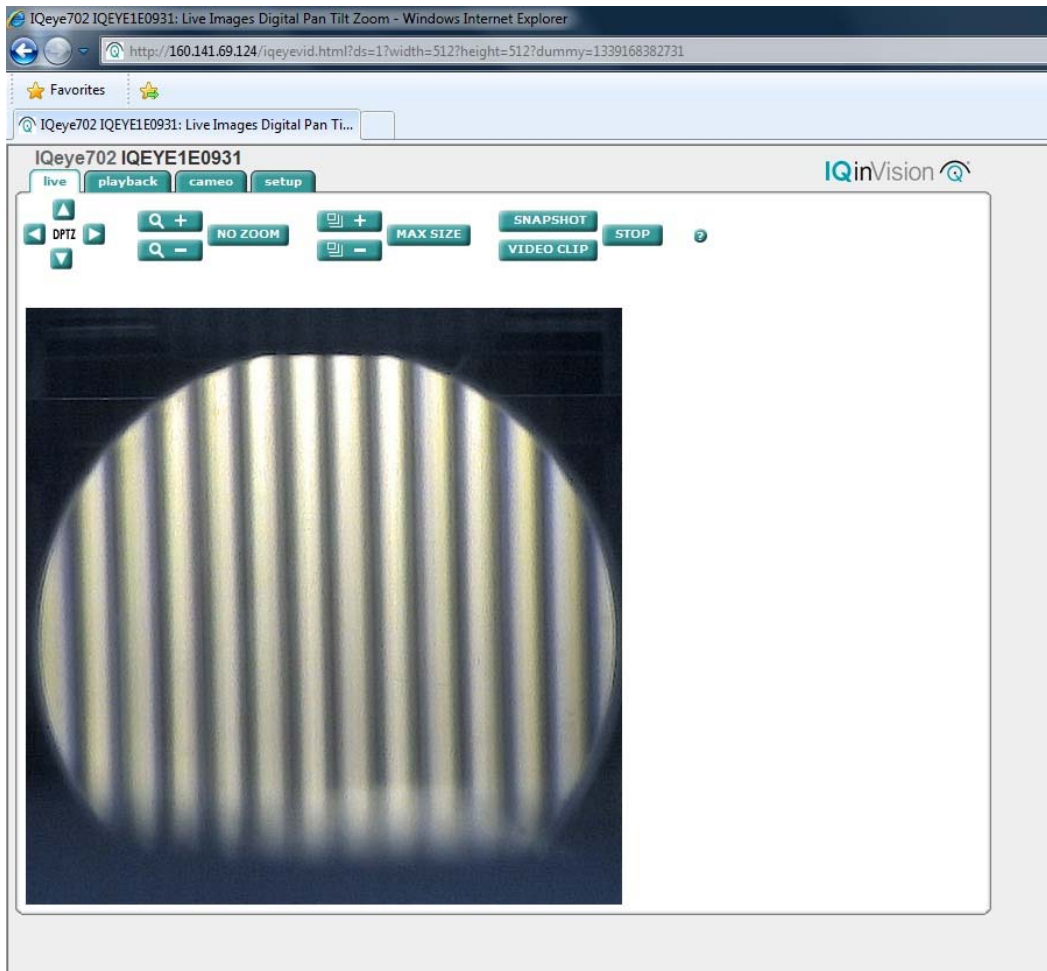


Figure 2. 'Live' view tab.

The menu that opens when the viewer has been loaded can be seen above. Each tab has its own set of options. These tabs are: live, playback, cameo, and settings.

- i. The 'live' tab will open automatically once the viewer has loaded. It contains buttons for panning (labeled 'DPTZ'), zooming in and out, increasing the size of the image displayed, taking a snapshot, recording a video clip (labeled 'Video

Clip'), stopping the recording, and a help button (see Figure 2 above; the figure was taken after the image size was increased once).

Note: When the size of the image is changed it does not change the number of pixels in the image; the image is set to 512 by 512 pixels and will remain as such unless changed in the 'Setup' tab. It is recommended that this *not* be changed.

- ii. The 'playback' tab will ask that a Java plug-in be installed.

Attention: Do not click this tab; if it is clicked, choose 'cancel' to go back to the 'live' view.

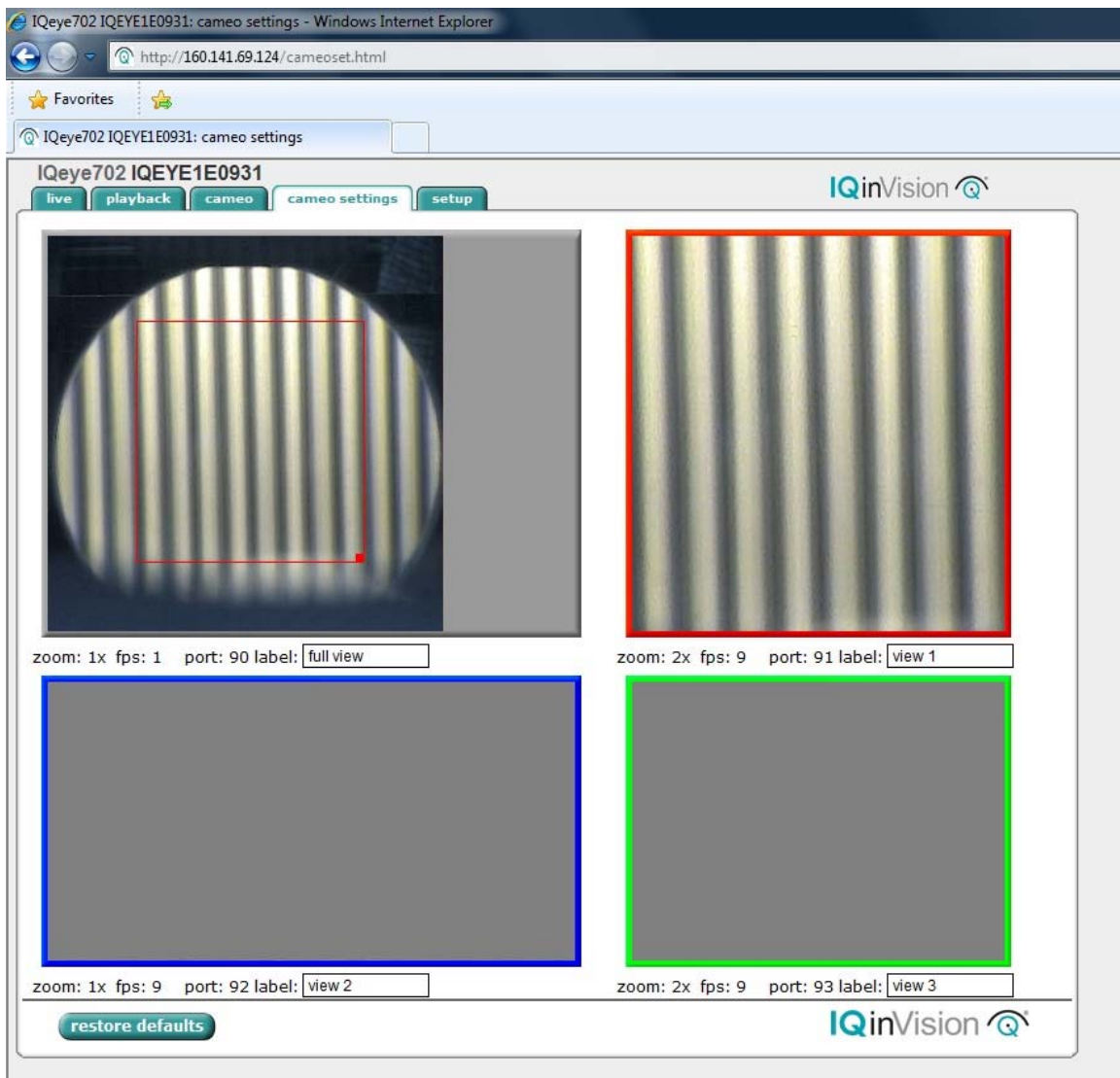


Figure 3. 'Cameo settings' tab.

- iii. The 'cameo' tab allows for simultaneous viewing of three sections of the camera view and creates a 'cameo settings' tab. This new tab allows the position and size of each cameo view to be set up separately from each other (see Figure 3 above).

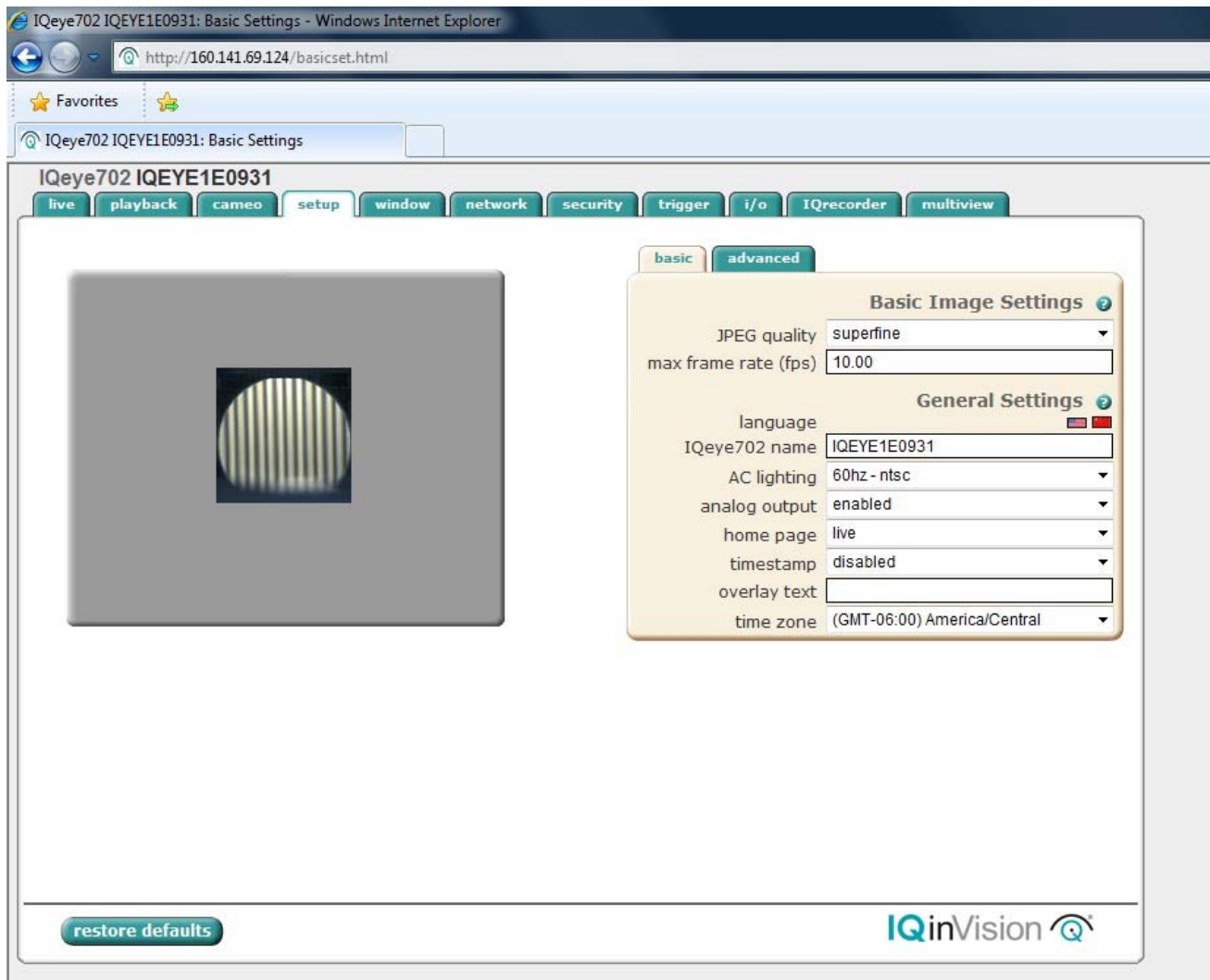


Figure 4. 'Setup' tab.

- iv. The 'setup' tab will open up many more tabs to adjust the various setting available to the user, from video and picture capture, triggers and timers for recording, and file storage and network options. The settings on any tab should not need to be changed, as they have all been set for optimum snapshot quality. The only settings that might need to be changed are the 'contrast' and 'light grabber' settings during the initial set-up and/or if the sample is tinted. These settings are found under the 'settings' tab, under the 'advanced' tab (see Figure 4 above).

- v. If at any time the user is asked for a user name and password, enter 'root' and 'system', respectively.

3. Set Up

The position of the mirror, lens, grating, and camera are all in the proper position, and the camera has been properly set up in terms of alignment, focus, zoom, and aperture. None of these components should need to be adjusted too much, if at all; if adjustments must be made, follow the instructions at the end of this section.

- A. Turn on the computer (if needed) and log in.
- B. While the computer is starting up/logging in, plug the camera and the Ann Arbor distortion tester into the nearby power strip (if they have been unplugged) and turn on the power strip.
- C. Remove the lens cap from the camera if it is in place.
- D. Once the computer has logged in, open an Internet Explorer window and type 'http://160.141.69.124/' into the address bar.
- E. The control panel for the camera should show up on the screen in the 'live' view tab. See the figures above and the menu descriptions under System Components.
- F. It is recommended that the size of the camera view be increased at least once, but this is not necessary.
- G. Adjustment Instructions

This section will go over repositioning the components in order to obtain the best possible image, if necessary.

- i. The lens of the camera should be positioned as close as possible to the light source but not touching it.
- ii. The mirror may need to be tilted or rotated in order for the light to properly return through the system.
- iii. If the image is dim or clipped on either side, moving the camera sideways should provide a better image. If the picture is offset, rotating the camera should fix this.
- iv. If the image of the grating is overly elongated (ellipsoid, not round), the height of the camera, grating, and tester lens can be adjusted until the image is more circular. It is recommended that these be adjusted separately, starting with the lens.
- v. The image on screen should show between 12 and 14 lines. Change the distance between the tester lens and test grating (by moving the lens) until the correct number of lines are seen.
- vi. If there is easily apparent pincushion distortion in the image with no optical sample, check that the tester lens is oriented properly; do this by rotating the lens 180 degrees about the yaw axis (switch the front and back of the lens) and check the image onscreen.

For any other concerns about adjustment, see:

Jun 2006 – White paper on the use of the Ann Arbor Distortion Tester. Technical Memorandum 2006-06

4. Use

Now that the device is properly set up, it is time to record the distortion of the test lenses.

- A. It is recommended that a folder be created wherever the pictures are to be saved before the pictures are taken.
- B. First take the picture to use as the standard (undistorted image); click the 'snapshot' button on the camera 'live' view control panel.
- C. Save the picture to the desired location when the 'Save As' window opens.
- D. Place the optical sample in the desired position between the mirror and lens of the distortion tester using the optical sample holder or by holding it in position by hand.
- E. Adjust the position of the camera only if necessary.
- F. Rotate the gratings to the desired position using the handle. However, it is recommended that the grating remain vertical if easy use of the analysis software is desired.
- G. If use of the analysis software is desired, it is recommended that the lights in the room be dimmed, turned off, or otherwise prevented from affecting the image such that the background of image, the area around the lines, be as dark and as close to black as possible. Extra light or a brighter background will interfere with the analysis software's operation.
- H. When the grating and test lens are in the desired positions, click the 'snapshot' button on the camera 'live' view control panel.
- I. Save the picture to the desired location when the 'Save As' window opens.
- J. Repeat until no more pictures are needed.

5. Shut Down

When all testing is done the system needs to be reset for the next user.

- A. Quit the browser window with the camera control panel.
- B. If no analysis of the images is to be done, restart the computer; if analysis is to be done, follow the steps outlined in section six below before restarting the computer.
- C. Turn off the power strip.
- D. Put the lens cap on the camera.
- E. Remove the optical sample from the optical mount.

6. Analysis

Some analysis of the images can be done using the DistortionGUI application, which will analyze the images using Matlab and create image and data files for later use.

- A. To open this program, open the application named 'AnnArborDistortionTester' found on the desktop. This will open the window shown in Figure 5. This may take a minute or two.

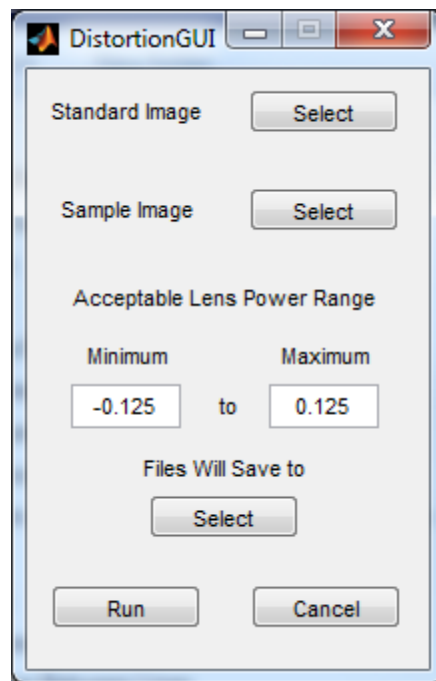


Figure 5. DistortionGUI window for image analysis.

- B. To analyze the images, do the following:
- Select the image to be used as a standard by clicking the first (top) 'Select' button and choosing the image from the directory.
 - Select the sample image containing the distortion by clicking the second 'Select' button and choosing the image from the directory.
 - Set the limit values that are acceptable for the lens power range of the optical sample in the two text boxes (default values shown in Figure 5).
 - All images and data, including those not displayed upon clicking 'Run,' can be saved to a specific location by clicking the third 'Select' button. Once the directory window has opened, select the folder where the data is to be saved. Be aware, however, that saving these images and files to a folder where there are already similar files from another analysis will overwrite any old files with the same name as a file to be created, without asking for confirmation to do so.

- v. Click 'Run' when the previous steps are complete. This will run the program and close the window 'DistortionGUI.' This may take a minute or two; a message stating the files were saved will appear when the program is finished running.
- C. Once the program has run some of the results will be displayed in four image windows and a text window that are now open; all of the results, including the numerical values for lens power, line number, and distance, will be saved to the file designated in step 6.B.iv. The text window that opens will display results on diopter values, line distances (in pixels), and line number. The images that do appear will include: a plot of the minimum and maximum distances between two lines for every pixel row in the sample, with a plot of the average distance for comparison; the sample image with one blue and two green lines; a surface plot of the lens power over an area of the sample; and the standard image with one blue line and two red lines. A help window will also appear to indicate if there were any errors or that the results files have been saved.
- i. The four images that open once the DistortionGUI has finished analyzing the images include:
 - a. The image window labeled 'Figure 4' shows the minimum distance between any two dark lines, in pixels, for every row of the sample image in blue; the maximum distance between any two lines for every pixel row is shown in red. The black line shows the average distance between two lines for the whole image. See Figure 6 for an example.

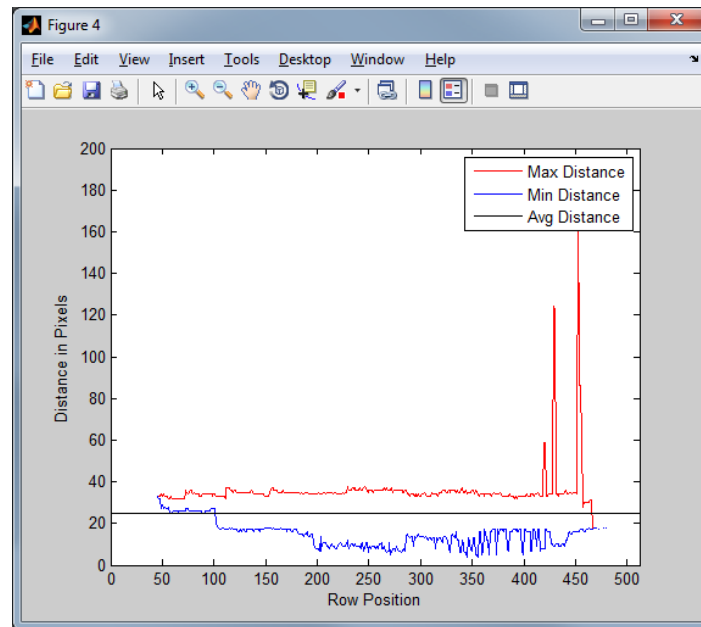


Figure 6. Window labeled 'Figure 4' that opens after running DistortionGUI. Note that the label of the x-axis is row position, not column position, so moving from left to right along this plot is

equivalent to moving from top to bottom of the distortion sample image. Therefore, in this plot the large jumps in value seen on the right are due to the quality of the image near the bottom of the distortion grating.

- b. The image window labeled 'Figure 6' shows the distortion sample image with two green lines and one blue line. The green lines define the area over which the optical sample's lens power was measured for the surface plot in image window 'Figure 8'. The blue line shows where the highest number of dark lines was counted. See Figure 7 for an example.

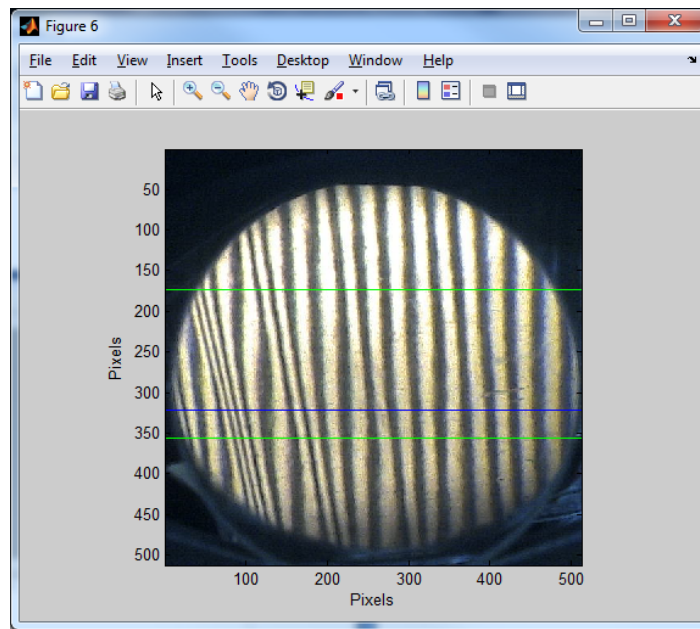


Figure 7. Window labeled 'Figure 6' that opens after running DistortionGUI.

- c. The image window labeled 'Figure 8' contains a 3-dimensional surface plot of the lens power of the optical sample over the area of the distortion sample image between the two green lines (shown in the image window labeled 'Figure 6'). See Figure 8 for an example.

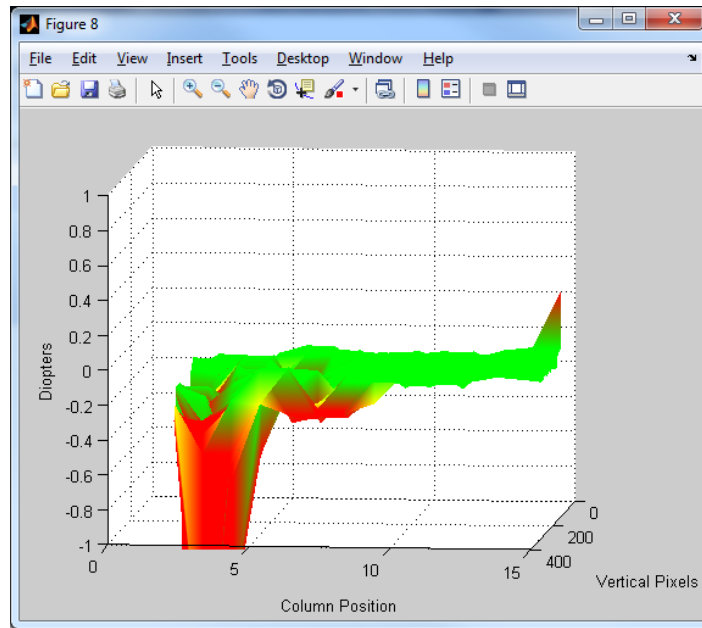


Figure 8. Window labeled 'Figure 8' that opens after running DistortionGUI.

- d. The image window labeled 'Figure 9' shows the standard sample image with two red lines and one blue line. The red lines indicate the rows used to measure line tilt and angle, and the blue line shows where the highest number of dark lines was counted. See Figure 9 below for an example.

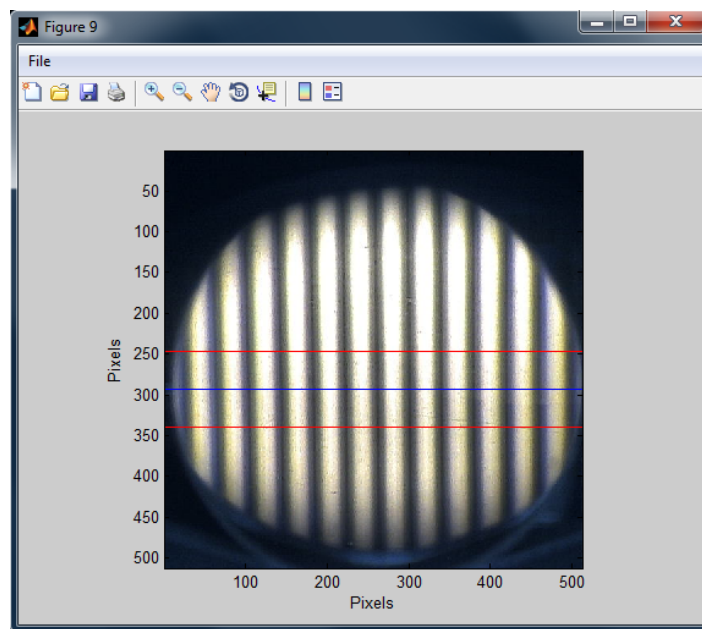


Figure 9. Window labeled 'Figure 9' that opens after running DistortionGUI.

- ii. The main numerical results found in the file called 'Main Results File' include those for the lens power and diopter values, the data on the dark lines of the sample, and the data for the dark lines of the standard. This is the text window that opens upon running the DistortionGUI.
 - a. The diopter values include: the locations of the green lines marking the edges of the surface plot and the size of this range; the minimum, maximum, average, median, and standard deviation of the diopter values; and the equation used to determine the diopter values, derived from the number of dark lines counted in the standard. This section will also include a statement of whether or not the image passes or fails the lens power test, or indicate that the image is borderline passing and needs to be examined further.
 - b. The data for the sample and standard images both include: the maximum number of dark lines counted in the image and the location of where this number of lines was found by pixel row; and the maximum, minimum, average, median, and standard deviation of the distances between each line in pixels.
 - c. After the lens power test is done the DistortionGUI will automatically run a test on the distances between the dark lines of the sample image. The results of this test (including the passing value, the number of failures if the test fails, and the worst failing value) will be displayed along with a statement of whether or not the sample passes or fails the distance test, or if the image is borderline.
- iii. Also created but not shown upon running the DistortionGUI are images and plots showing other data about the images, including trough and dark line locations, the distances between them, and any horizontal shifts or angles of the dark lines. These images, as well as the text file 'Secondary File,' are saved to the folder selected in step 6.B.v. The text file 'Secondary File' includes explanations of every image, including those displayed once DistortionGUI has finished.



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